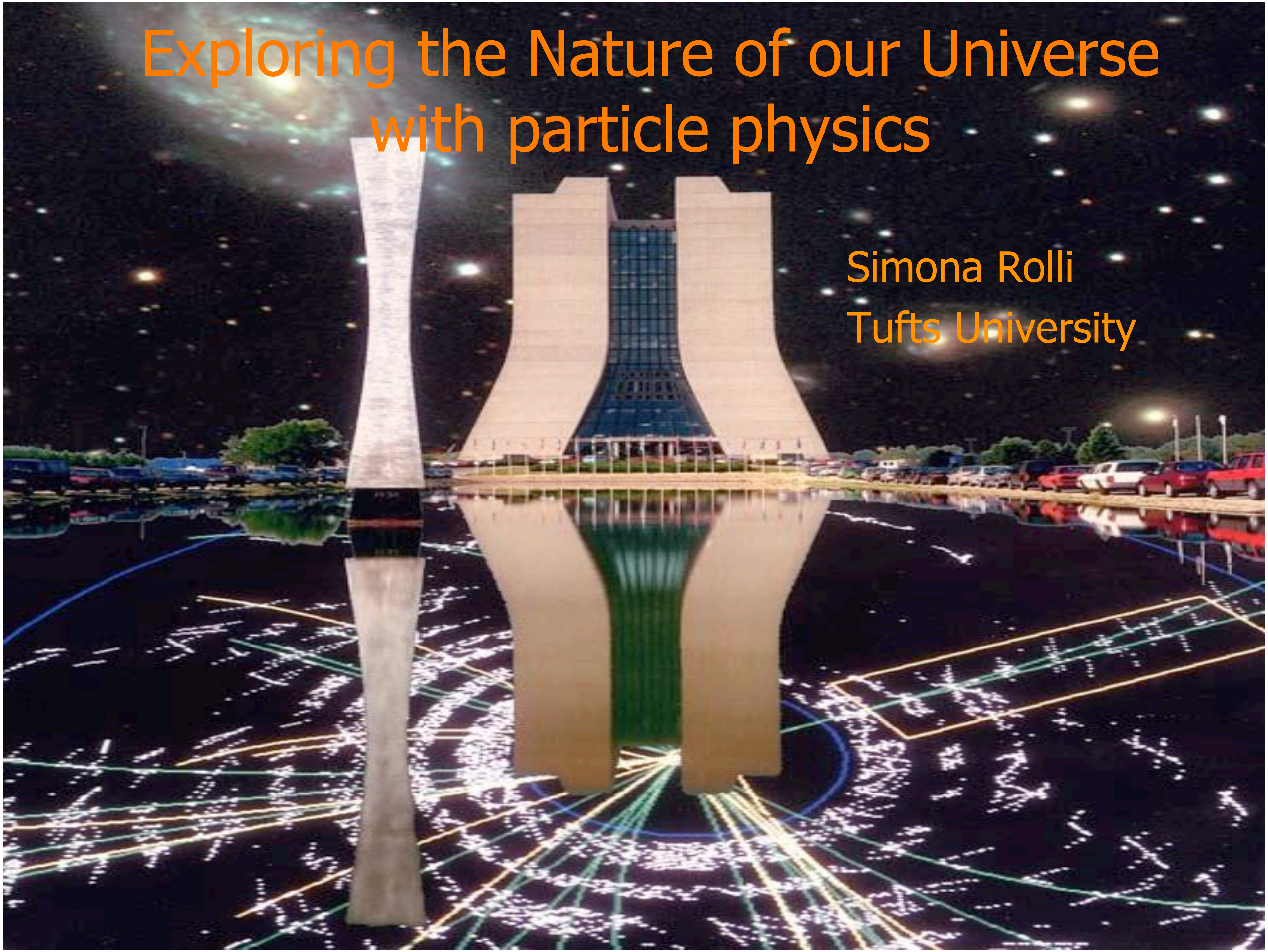
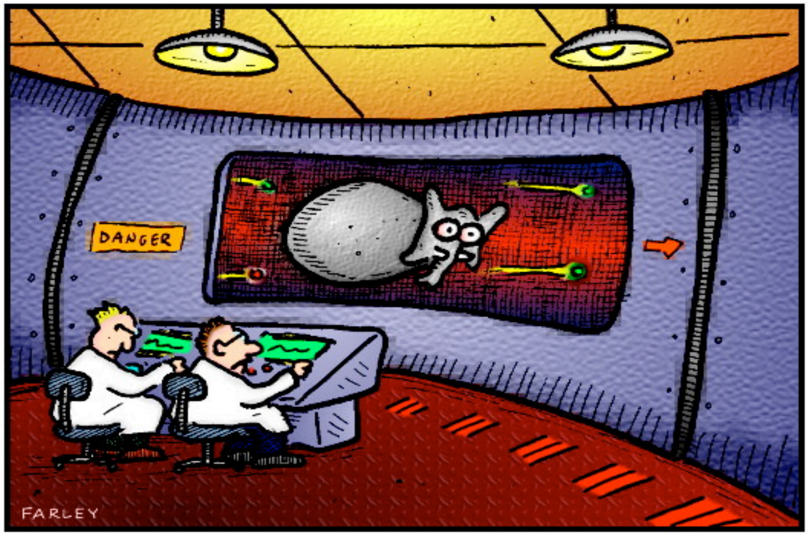
Exploring the Nature of our Universe with particle physics

Simona Rolli
Tufts University



Introduction



Deep within the atomic supercollider, the search continues for the elusive elephantino.

A (small) community of scientists is building more and more powerful machines to explore the intimate nature of matter and answer some of the fundamental questions about our Universe

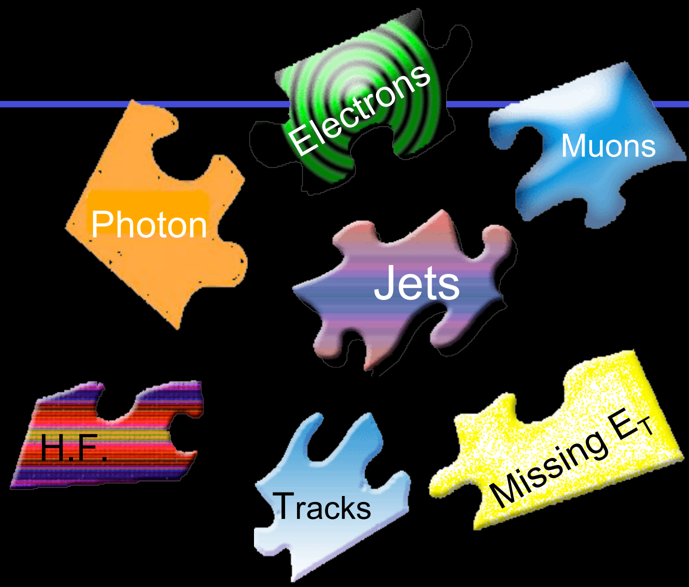
Particle Physics has evolved from small laboratory experiments to world-wide enterprises lasting several years and involving several thousand people per experiment

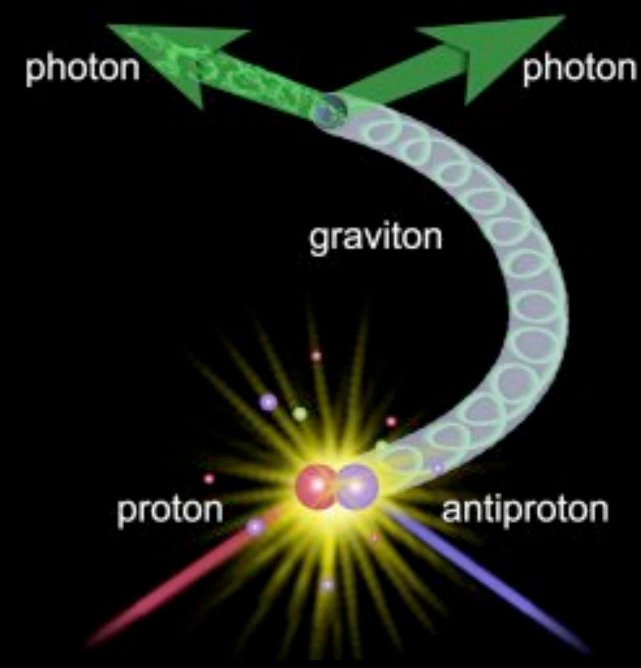
Not all the questions have received an answer yet.

The search is still on….

Outline of the talk

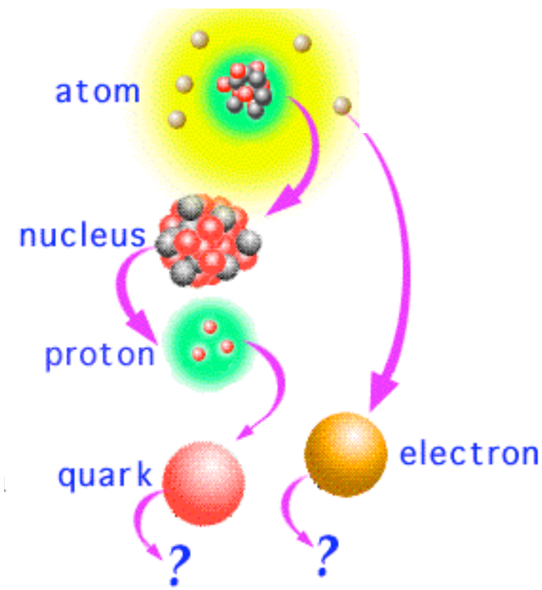
- **What is the Universe made of ?**
  - **Elementary particles**
  - **Energy and matter**
  - **Forces**
- **The Experimental Apparatus**
  - **Accelerators and Particle Detectors**
  - **Going back in time**
  - **History of Colliders**
  - **The Future**
- **Who is a Particle Physicist?**





What is the World made of?

- The matter of the world is made from a few fundamental building blocks of nature.
- The word **"fundamental"** is key here. By fundamental building blocks we mean objects that are **simple and structureless** -- not made of anything smaller.



- Everything we see is made of molecules or chains of atoms
- Atoms contain a nucleus surrounded by electrons
- In the nucleus there are protons and neutrons
- Protons and neutrons are bound states of quarks and gluons

The Atom

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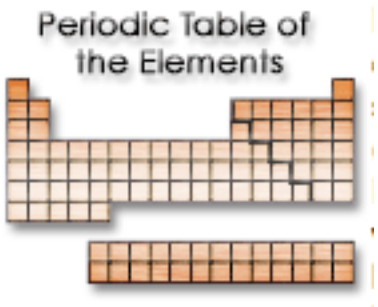

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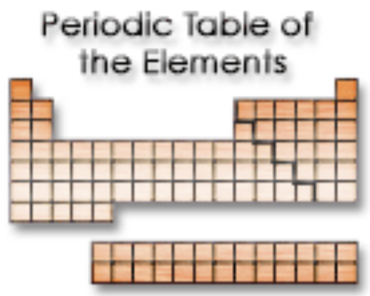
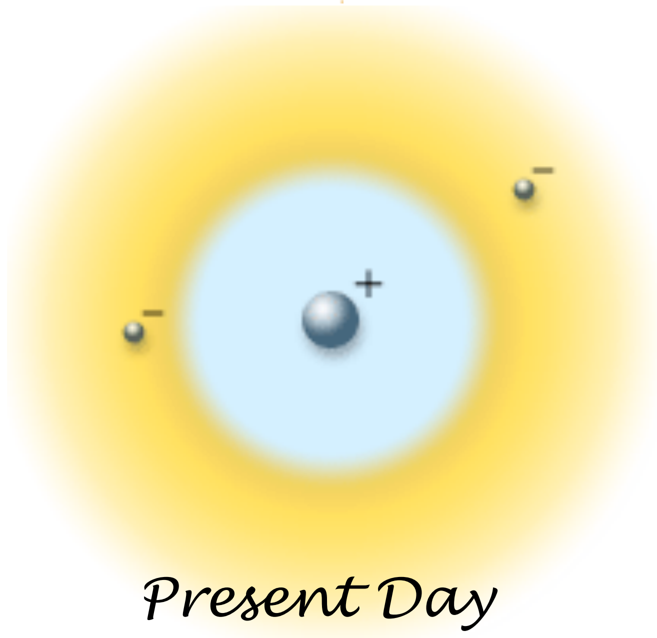


This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined which atoms had which chemical properties.

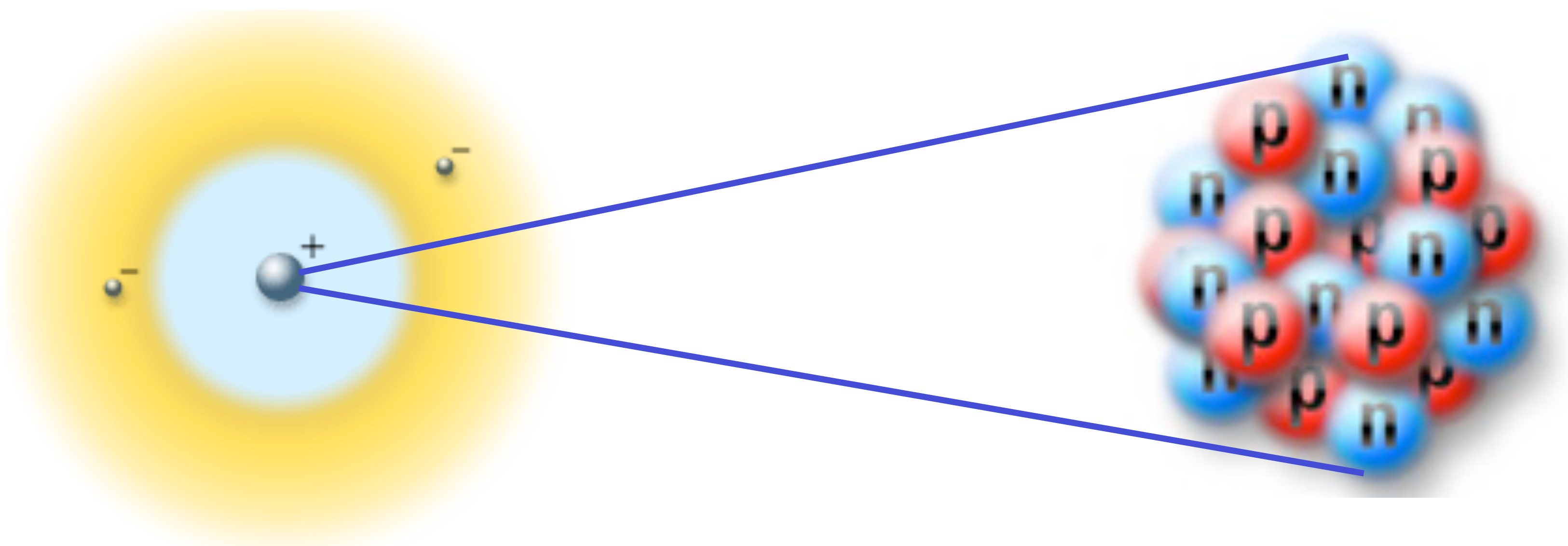


Inside the Atom

- Experiments which "looked" into an atom using particle probes indicated that atoms had structure and were not just squishy balls. These experiments helped scientists determine that atoms have a tiny but dense, positive nucleus and a cloud of negative electrons (e^-).

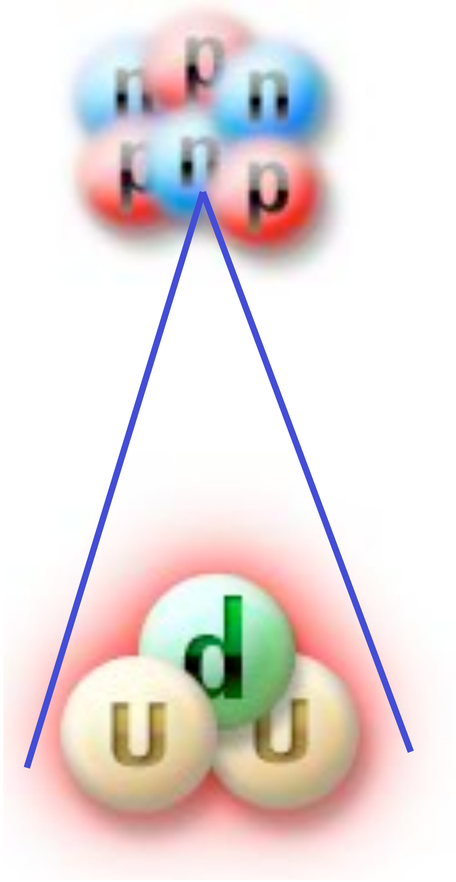
- **Is the Nucleus fundamental ?**

- Because it appeared small, solid, and dense, scientists originally thought that the nucleus was fundamental. Later, they discovered that it was made of protons (p^+), which are positively charged, and neutrons (n), which have no charge.



Inside Protons and Neutrons

- **Are protons and neutrons fundamental?**

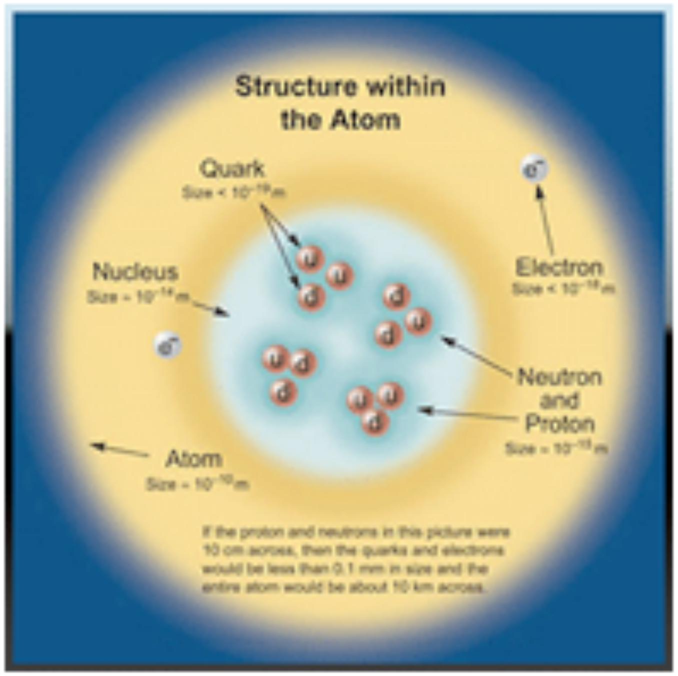


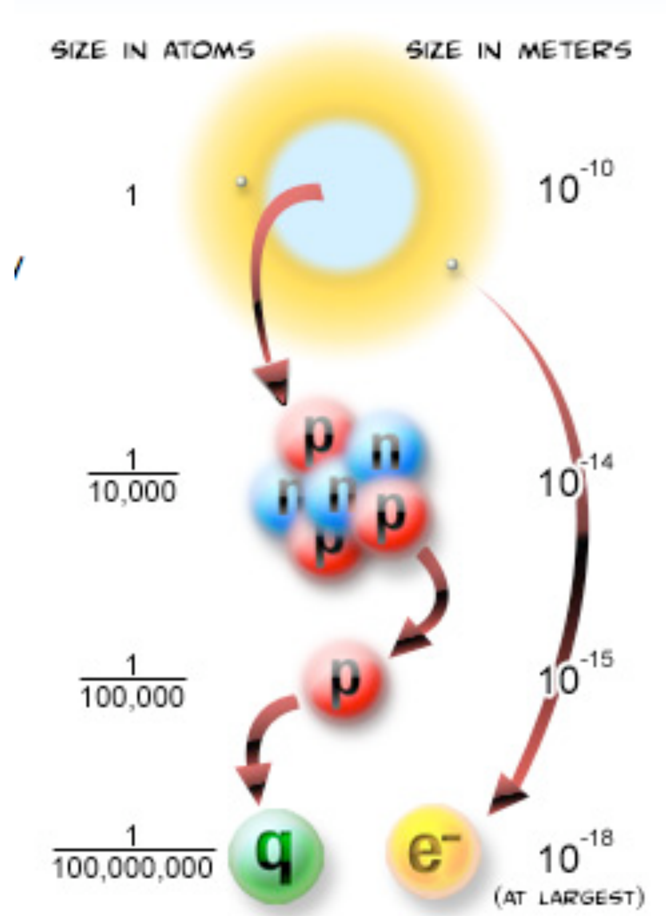
Physicists have discovered that protons and neutrons are composed of even smaller particles called **quarks**.

As far as we know, quarks are like points in geometry. They're not made up of anything else.

After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental.

The modern Atom





The Search

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- Physicists, though, are constantly looking for new particles….

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H^2O

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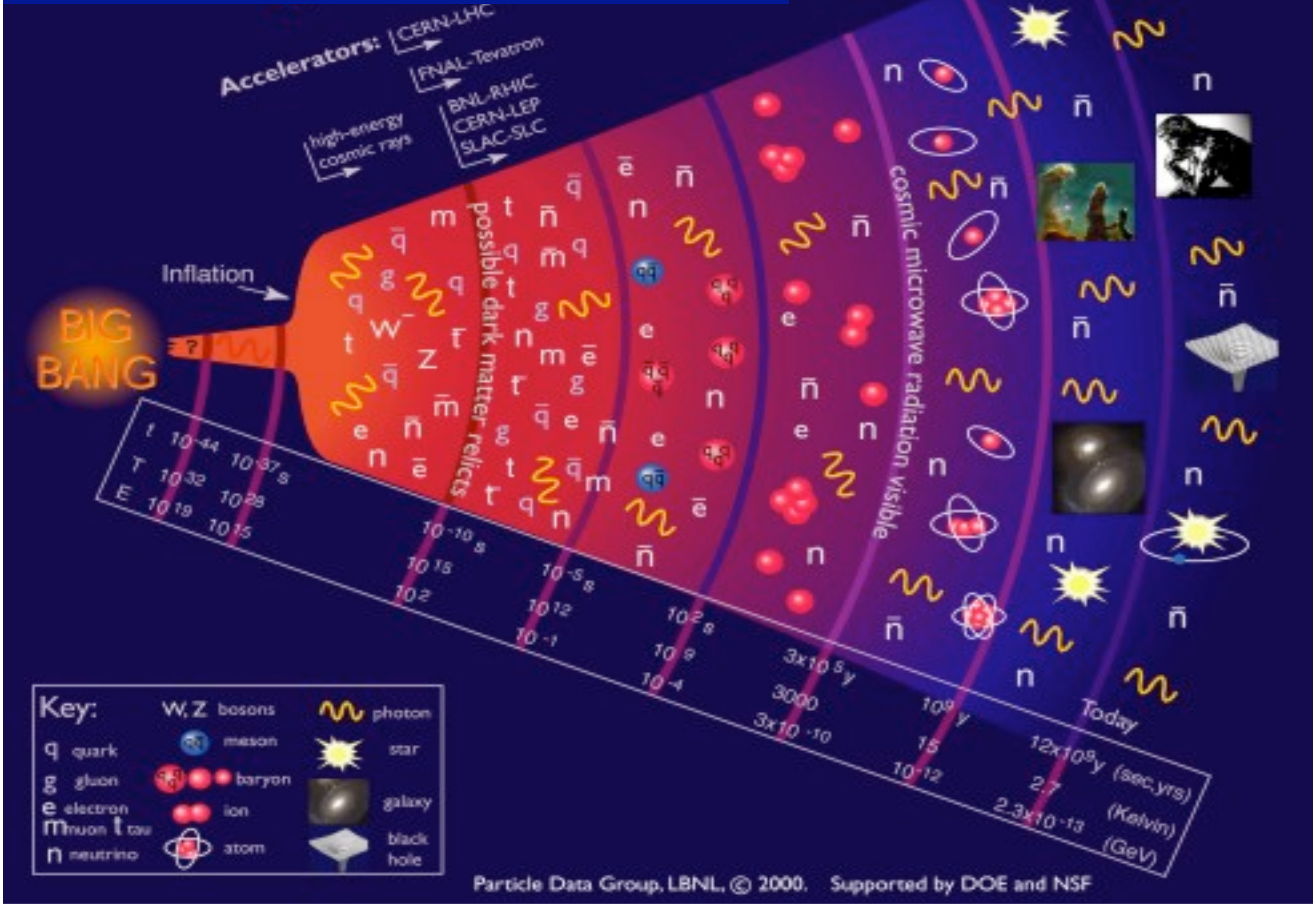
Physicists have found an amazing world of particles and have studied the interactions among them, while traveling back in time…..

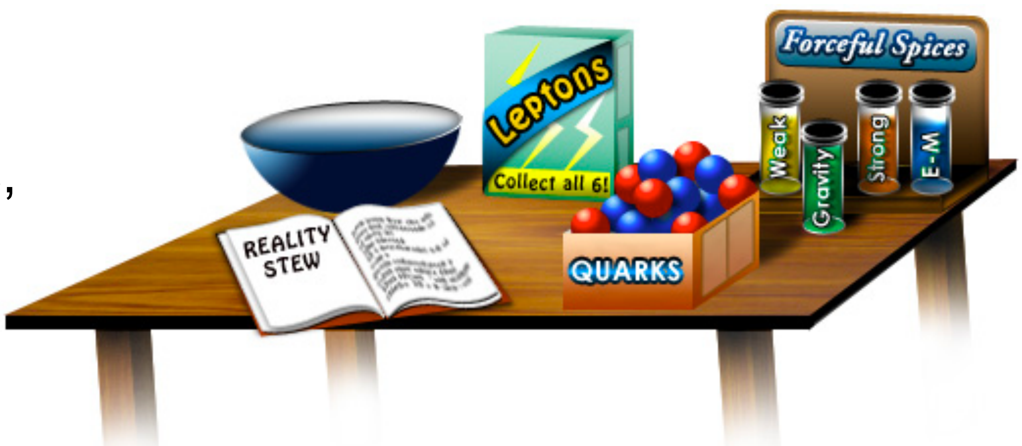
Particles and Time



The Standard Model of Particle Physics

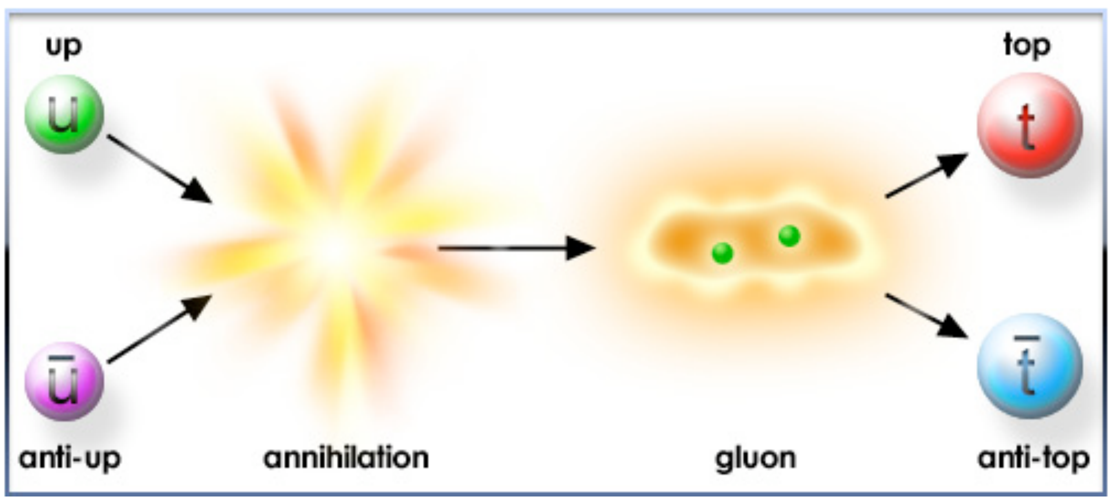
- Physicists have developed a theory called **The Standard Model** that explains what the world is and what holds it together. It is a simple and comprehensive theory that explains all the hundreds of particles and complex interactions with only:
  - **6 quarks**.
  - **6 leptons**. The best-known lepton is the electron.
  - **Force carrier particles**, like the photon.

All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.



Matter and Antimatter

- For every type of matter particle we've found, there also exists a corresponding **antimatter** particle, or **antiparticle**.
- Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges.
  - For instance, a proton is electrically positive whereas an antiproton is electrically negative.
- Gravity affects matter and antimatter the same way because gravity is not a charged property and a matter particle has the same mass as its antiparticle.



Antimatter

- The idea of antimatter is strange, made all the stranger because the universe appears to be composed entirely of matter. Antimatter seems to go against everything we know about the universe.

- If antimatter and matter are exactly equal but opposite, then why is there so much more matter in the universe than antimatter?

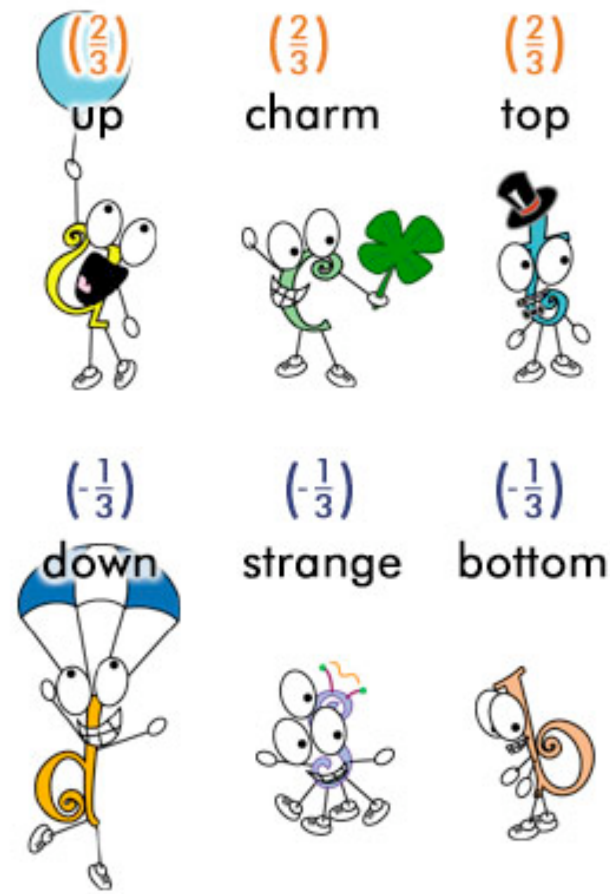
- Well... **we don't know**. It is a question that keeps physicists up at night.

- We think that for some reason which we still have to find, at the very initial moments of the Universe, this asymmetry between matter and anti-matter developed and was there to stay!

Quarks

Quarks are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks.

- There are **six quarks**, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)
- Quarks have the unusual characteristic of having a **fractional** electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge.
- The most elusive quark, **the top quark**, was discovered in 1995 after its existence had been theorized for 20 years.



Hadrons

- Like social elephants, quarks only exist in groups with other quarks and are never found alone.
- Composite particles made of quarks are called HADRONS

MESONS

...contain one quark (q) and one antiquark ($\bar{q}$).

One example of a meson is a pion (π^+), which is made of an up quark and a down anitiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion (π^-) is made up a down quark and an up antiquark.

BARYONS

...are any hadron which is made of three quarks (qqq).

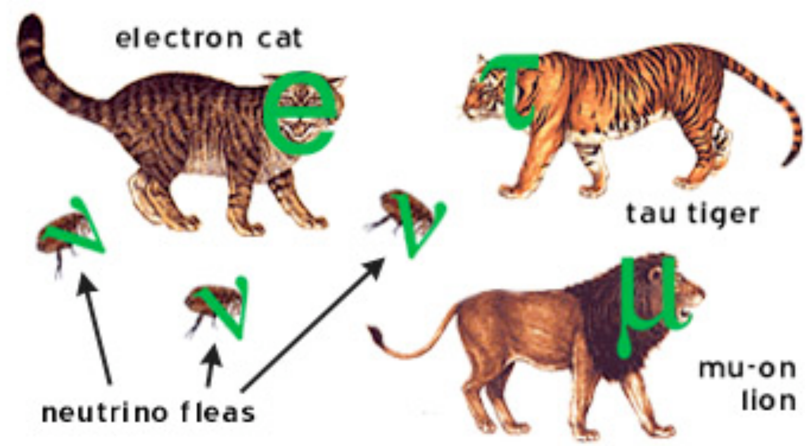
Because they are made of two up quarks and one down quark (uud), **protons** are baryons. So are **neutrons** (udd).

Leptons

- The other type of matter particles are the **leptons**.
- There are six leptons, three of which have electrical charge and three of which do not.
- They appear to be point-like particles without internal structure.
- The best known lepton is the **electron** (e^-). The other two charged leptons are the **muon**(μ) and the **tau**(τ), which are charged like electrons but have a lot more mass.
- The other leptons are the three types of **neutrinos** (ν). They have no electrical charge, very little mass, and they are very hard to find.

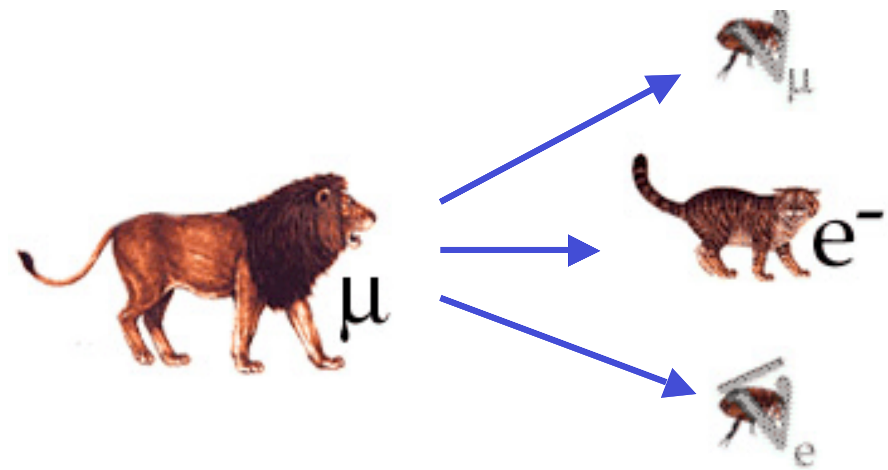
Quarks are sociable and only exist in composite particles with other quarks, whereas leptons are solitary particles.

Think of the charged leptons as independent cats with associated neutrino fleas, which are very hard to see.



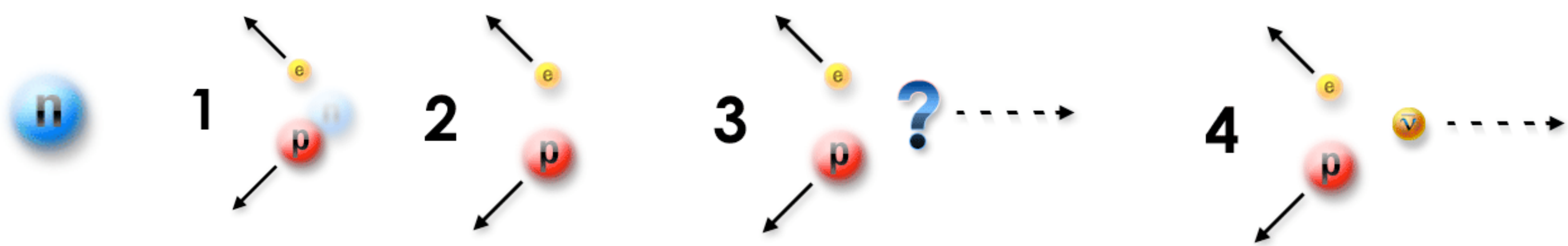
Lepton Decay

- The heavier leptons, the muon and the tau, are not found in ordinary matter at all. This is because when they are produced they very quickly **decay**, or transform, into lighter leptons. Sometimes the tau lepton will decay into a quark, an antiquark, and a tau neutrino. Electrons and the three kinds of neutrinos are stable and thus the types we commonly see around us.



Neutrinos

- Neutrinos are a type of lepton. Since they have no electrical or strong charge they almost never interact with any other particles.
- Most neutrinos pass **right through the earth** without ever interacting with a single atom of it.
- Neutrinos are produced in a variety of interactions, especially in particle decays. In fact, it was through a careful study of radioactive decays that physicists hypothesized the neutrino's existence.
    - For example: **(1)** In a radioactive nucleus, a neutron at rest (zero momentum) decays, releasing a proton and an electron. **(2)** Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero, which the observed proton and electron clearly do not. **(3)** Therefore, we need to infer the presence of another particle with appropriate momentum to balance the event. **(4)** We hypothesize that an antineutrino was released; experiments have confirmed that this is indeed what happens.



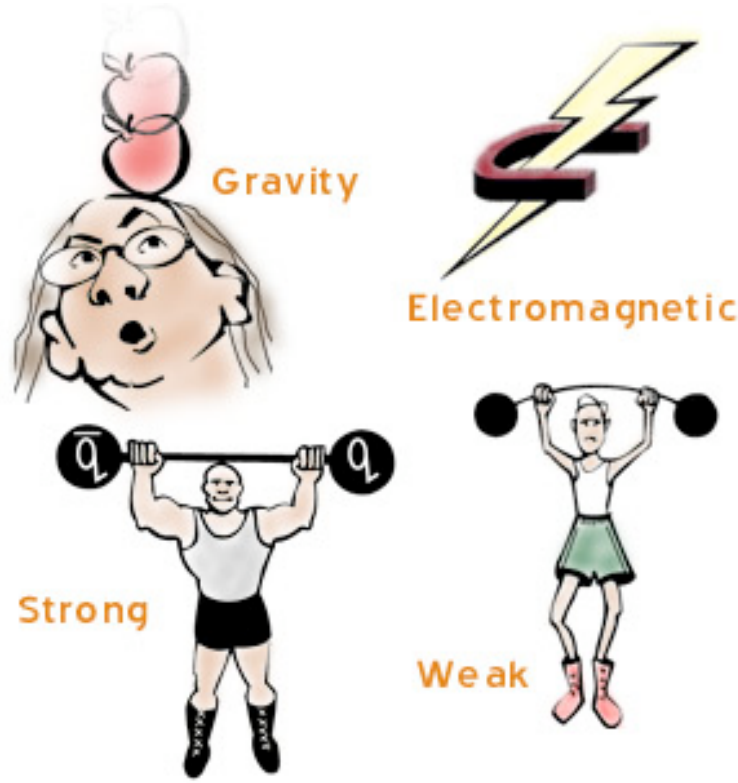
Summary

- What are protons made of?
- What are electrons made of?
- What are mesons made of?

- What are the fundamental particles?

Forces

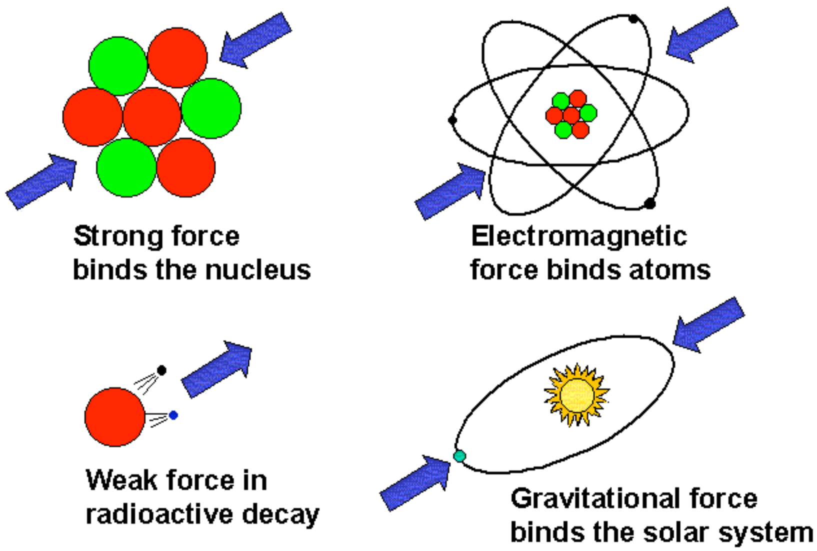
- So, the world is made of quarks and leptons…
- What holds these particle together?
- The universe, which we know and love, exists because the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation.
- There are four fundamental interactions between particles, and **all forces in the world can be attributed to these four interactions!**



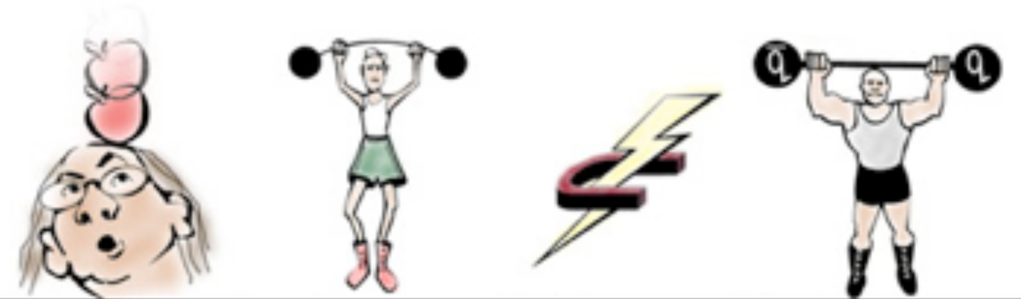
At a fundamental level, a force isn't just something that happens to particles. It is a thing which is passed between two particles. There are FORCE CARRIERS! New particles!

Forces

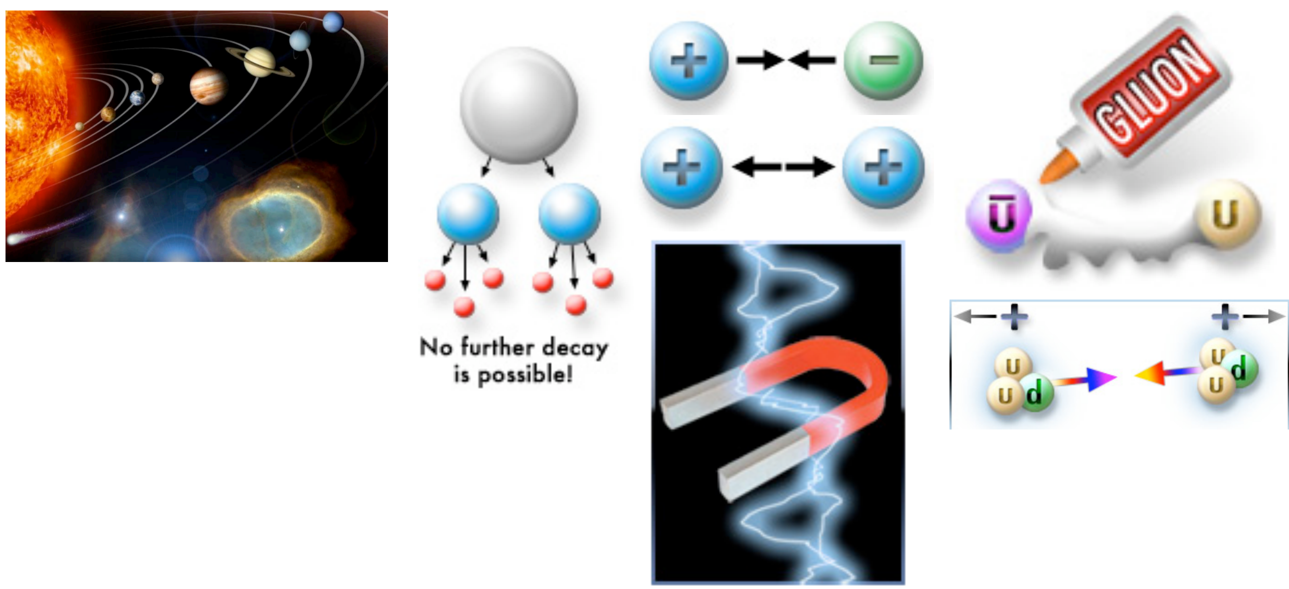
- A particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force.
- For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.



Forces



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

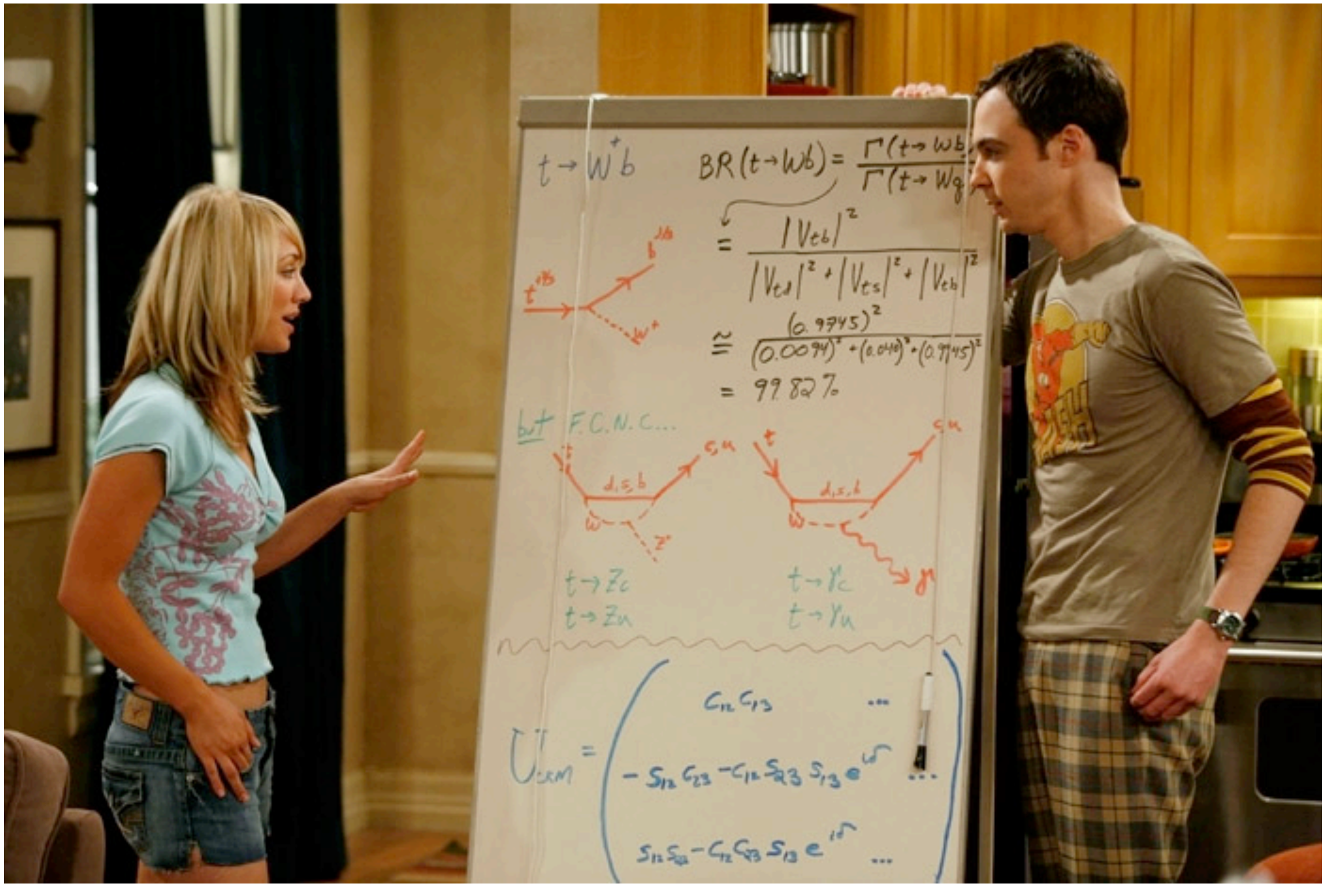


Summary 2

- How many forces are in nature?

How do we know any of this?

- All of this scientific theory may start to look like magic, but it's important to realize that physicists do not just sit around and make up this stuff.
- They test their hypotheses, and create new theories from the results of their experiments.

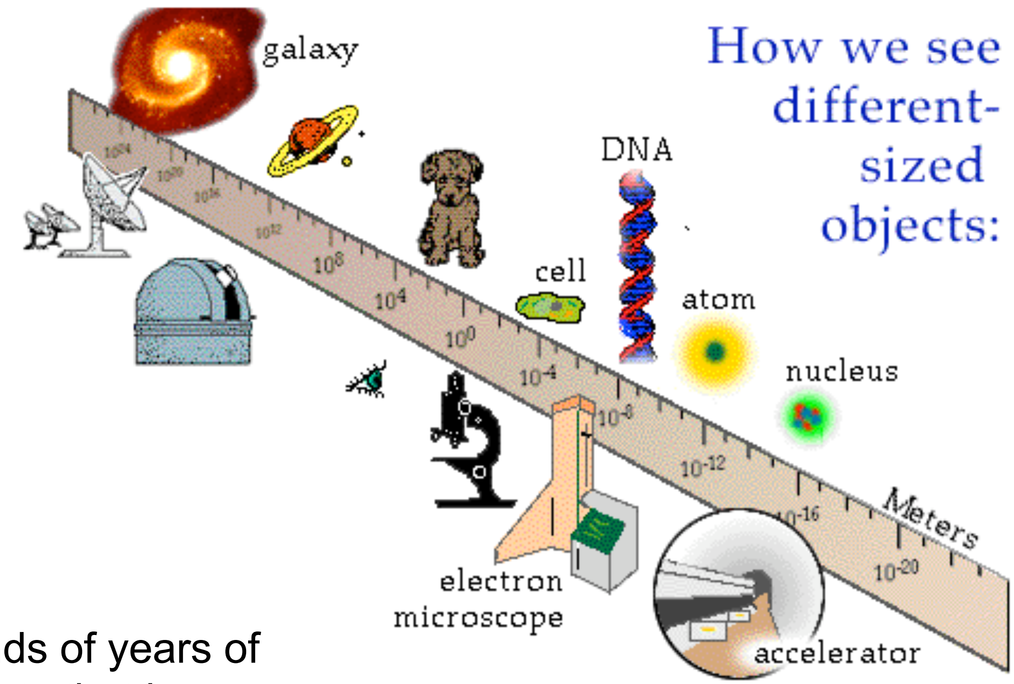


How do we know any of this?

- To test theories, physicists put together experiments and use what they already know to find out what they do not know.

How do we know any of this?

- These experiments may be simple, or they may be huge and complicated.



- The Standard Model rises out of thousands of years of scientific inquiry, but most of the experiments that have given rise to our current conception of particle physics have occurred relatively recently. The story of how physicists experiment to test and create theories in modern particle physics is one which starts less than a hundred years ago...

Timeline of Particle Discoveries

1895 The **electron** is discovered, except electrons are called **cathode rays** by their discoverer.

1896 **X rays** and other forms of radioactivity are observed

1899 **Alpha particles** are discovered, and later shown to be helium nuclei consisting of two neutrons and two protons.

1911 Nuclear model of **atom** with heavy nucleus in the middle and light electrons orbiting around it, is proposed, and becomes accepted.

1911 **Electron charge** measured in an oil drop experiment indicates that all electrons carry the same electric charge.

1932 The **neutron** directly observed in an experiment for first time.

1932 The **positron**, predicted by a theorist in 1928, is discovered.

1934 Radioactive **nuclei** produced in the laboratory.

1937 The **muon**, a charged lepton like the electron only heavier and hence unstable, is discovered.

1947 Two **charged pi mesons**, with positive and negative charge, are discovered.

1950 The **neutral pi meson** is discovered.

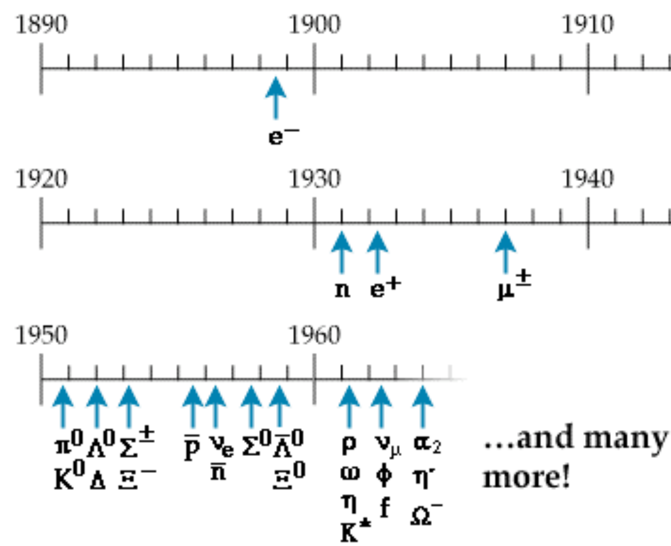
1953 The **lambda baryon** and **K meson** are discovered.

1956 The **electron neutrino**, predicted by theory in 1930, is confirmed to exist.

1950s-1960s Lots of **baryons** and **mesons** being discovered, and their properties occur in regular patterns that look as if baryons and mesons are made of smaller building blocks. Physicists exhibit a tendency to name new particles after letters in the Greek alphabet.

1961 The **muon neutrino** is discovered and shown to be a different particle from the electron neutrino..

1963 **Quark** theory postulates that protons are made of smaller particles that carry charges that come in thirds of the electron charge. The three flavors of quarks are given names: **up**, **down** and **strange**.



Timeline of Particle Discoveries

1970s Deep inelastic scattering and other experiments reveal more of the quark structure inside protons and other hadrons.

1974 A fourth flavor of quark, named **charm**, is detected in a newly discovered meson called the **J** (aka the yor **Psi**).

1975 The **tau lepton** is discovered, making a triplet of charged leptons with the electron and muon, leading to predictions of a **tau neutrino** to accompany the electron neutrino and the muon neutrino.

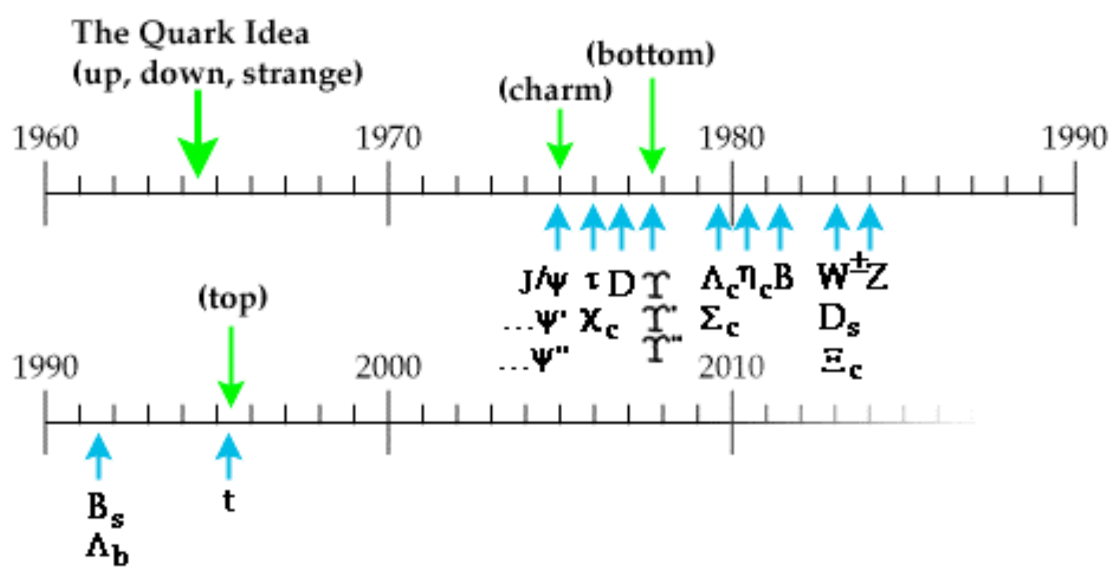
1979 A fifth flavor of quark, named **bottom**, is detected in the newly discovered Upsilon meson. This pattern leads particle physicists to believe they will find a sixth and final flavor of quark some day. This predicted last flavor of quark is called **top**.

1983 The massive gauge bosons that carry the weak nuclear force, called the $\mathbf{W^+}$,$\mathbf{W^-}$ and $\mathbf{Z^0}$, are discovered and the Standard Model of Particle Physics is confirmed.

1989 The lifetime of the $\mathbf{Z^0}$ weak nuclear gauge boson is measured, and agrees precisely with there being exactly three kinds of neutrinos, and no more.

1995 The **top quark** is finally directly observed and measured, confirming the predictions of theorists that there are six flavors of quarks, as described in the Standard Model.

Future The search goes on for the **Higgs boson** (the only particle predicted by the Standard Model that hasn't been seen yet), for **supersymmetric particles** predicted by string theory, for proton decay and for **magnetic monopoles** predicted by Grand Unified Theories, and **new kinds of exotic unpredicted particles** is ongoing. Perhaps in a few years there will be some more interesting entries for this page. Come back later and see.



Mass and Energy

Quite often, physicists want to study massive, unstable particles that have only a fleeting existence (such as the very massive top quark.)

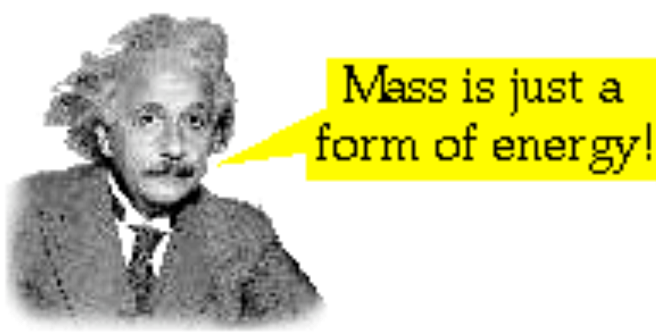
However, all that physicists have around them in the every day world are very low-mass particles.

How does one perform this amazing feat of using particles with lesser mass to obtain particles of greater mass?

You know Albert Einstein's famous equation that where E is the energy, m is the mass, and c is the speed of light.

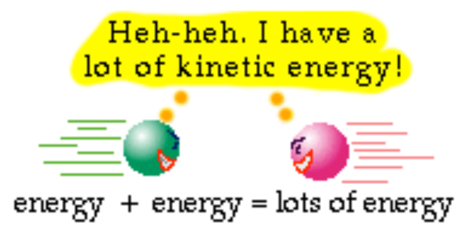
$$E = mc^2$$

Therefore,



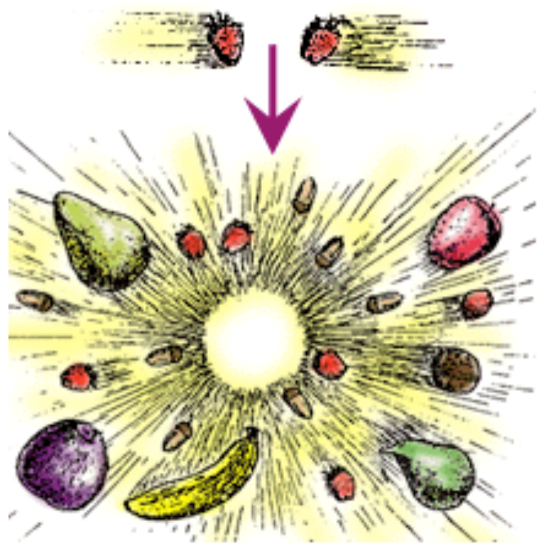
Colliders

When a physicist wants to use particles with low mass to produce particles with greater mass, all she has to do is put the low-mass particles into an accelerator, give them a lot of kinetic energy (speed), and then collide them together.
During this collision, the particle's kinetic energy is converted into the formation of new massive particles.



It is through this process that we can create massive unstable particles and study their properties.

It is as if you stage a head-on collision between two strawberries and get several new strawberries, lots of tiny acorns, a banana, a few pears, an apple, a walnut, and a plum.

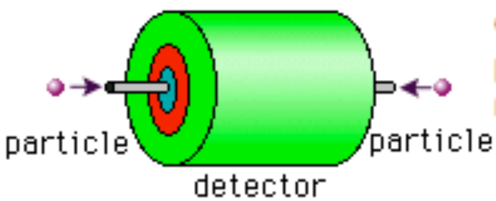


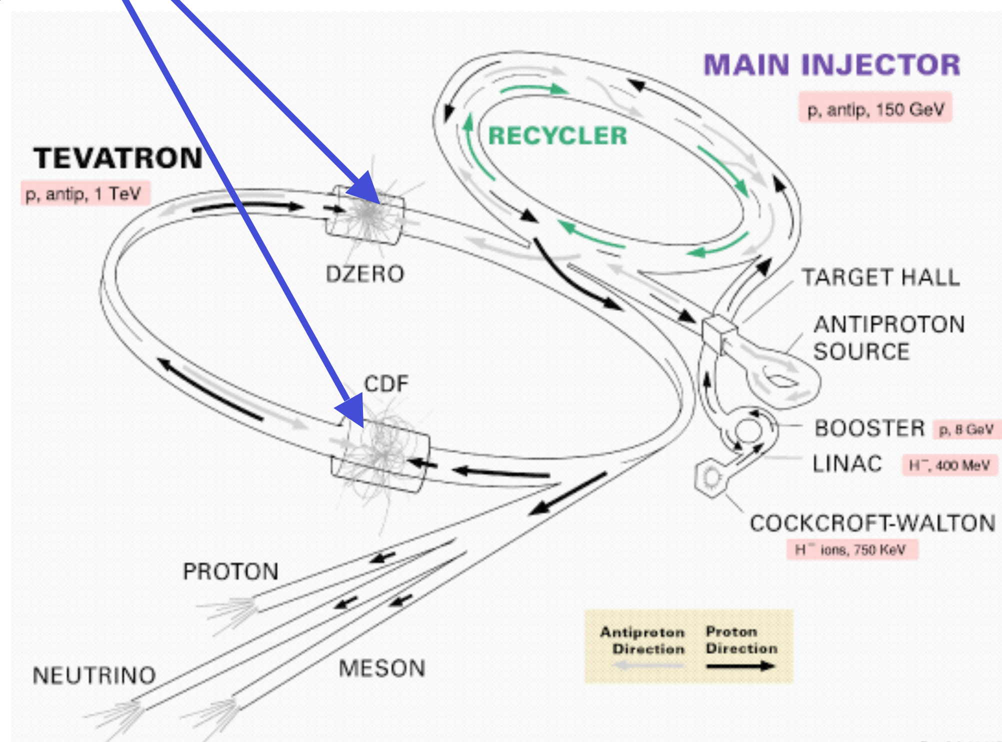
Accelerators

How do accelerators work?

Basically, an accelerator takes a particle, speeds it up using electromagnetic fields, and smashes the particle into a target or other particles.

Surrounding the collision point are detectors that record the many pieces of the event.





Today Accelerators

SLAC: Stanford Linear Accelerator Center, in California, discovered the charm quark (also discovered at Brookhaven) and tau lepton; ran an accelerator producing huge numbers of B mesons.

Fermilab: Fermi National Laboratory Accelerator, in Illinois, where the bottom and top quarks and the tau neutrino were discovered.

CERN: European Laboratory for Particle Physics, crossing the Swiss-French border, where the W and Z particles were discovered.

BNL: Brookhaven National Lab, in New York, simultaneously with SLAC discovered the charm quark.

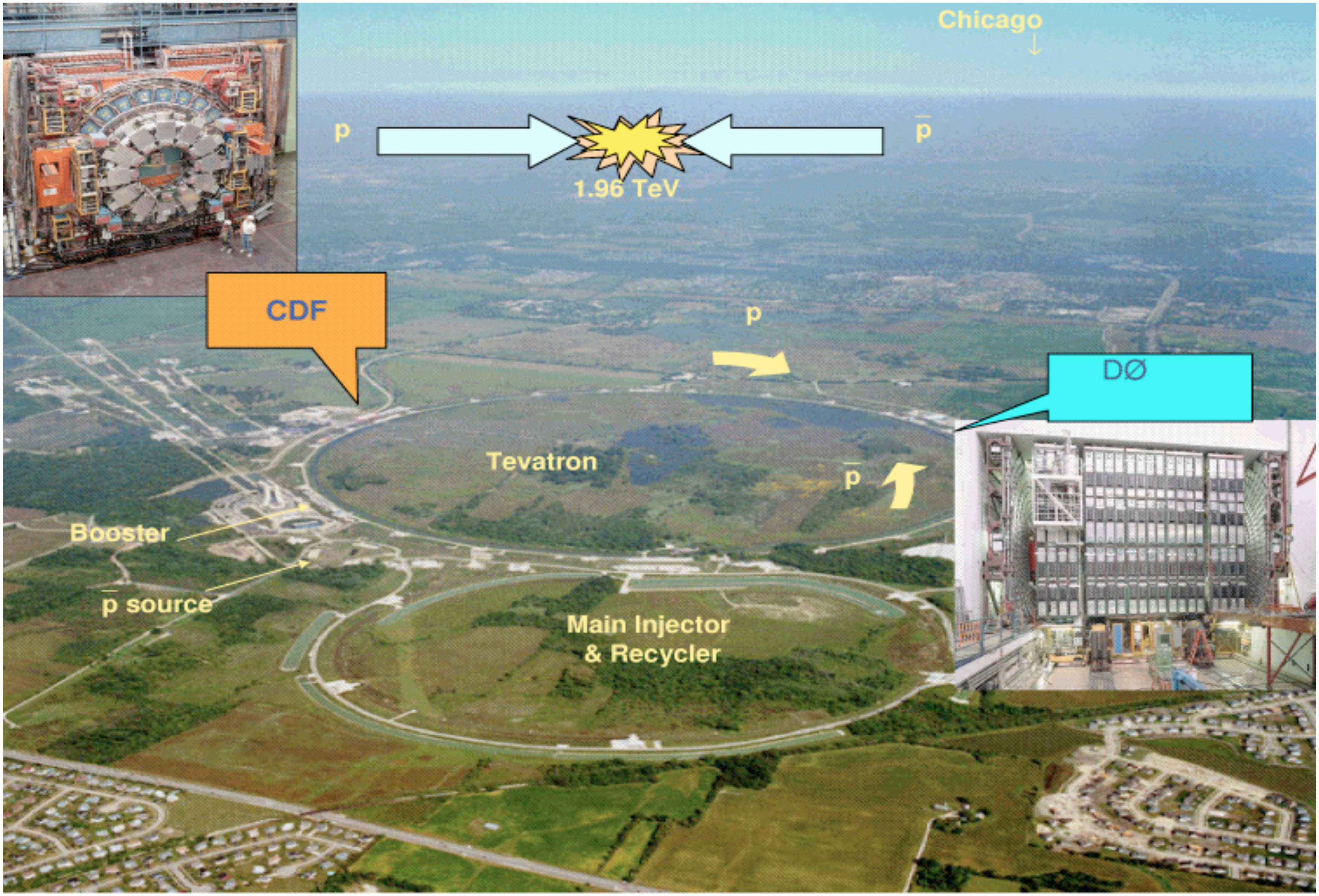
CESR: Cornell Electron-Positron Storage Ring, in New York. CESR performed detailed studies of the bottom quark.

DESY: Deutsches Elektronen-Synchrotron, in Germany; gluons were discovered here.

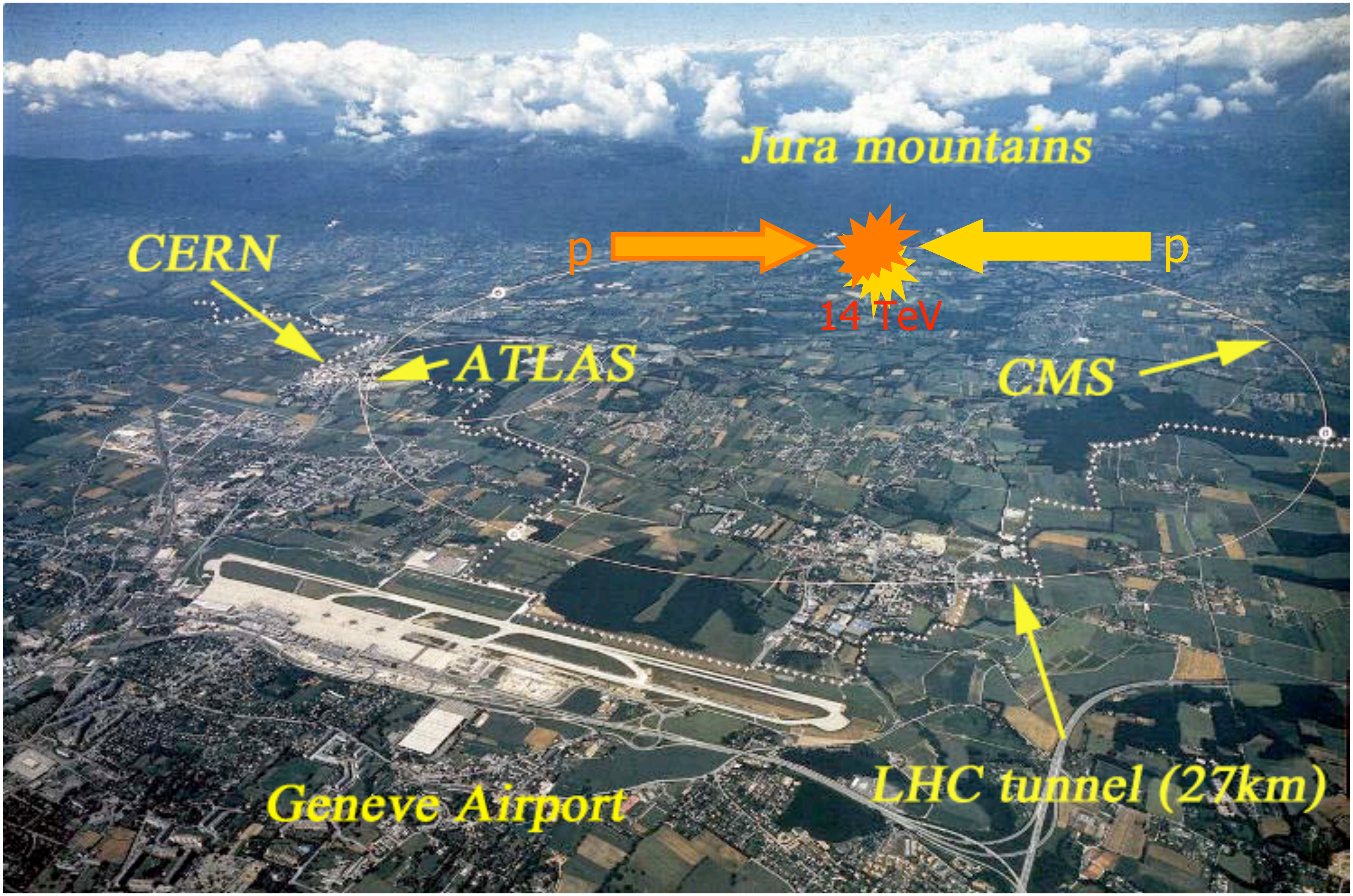
KEK: High Energy Accelerator Research Organization, in Japan, is now running an accelerator producing huge numbers of B mesons.

IHEP: Institute for High-Energy Physics, in the People's Republic of China, performs detailed studies of the tau lepton and charm quark.

The Fermilab Tevatron



CERN Large Hadron Collider



The Accelerator Chain (Fermilab)

An **electronvolt** (symbol: eV) is the amount of energy gained by a single unbound electron when it falls through an electrostatic potential difference of one volt. Very small amount of energy: 1 eV ≈ 1.602×10^{-19} J.

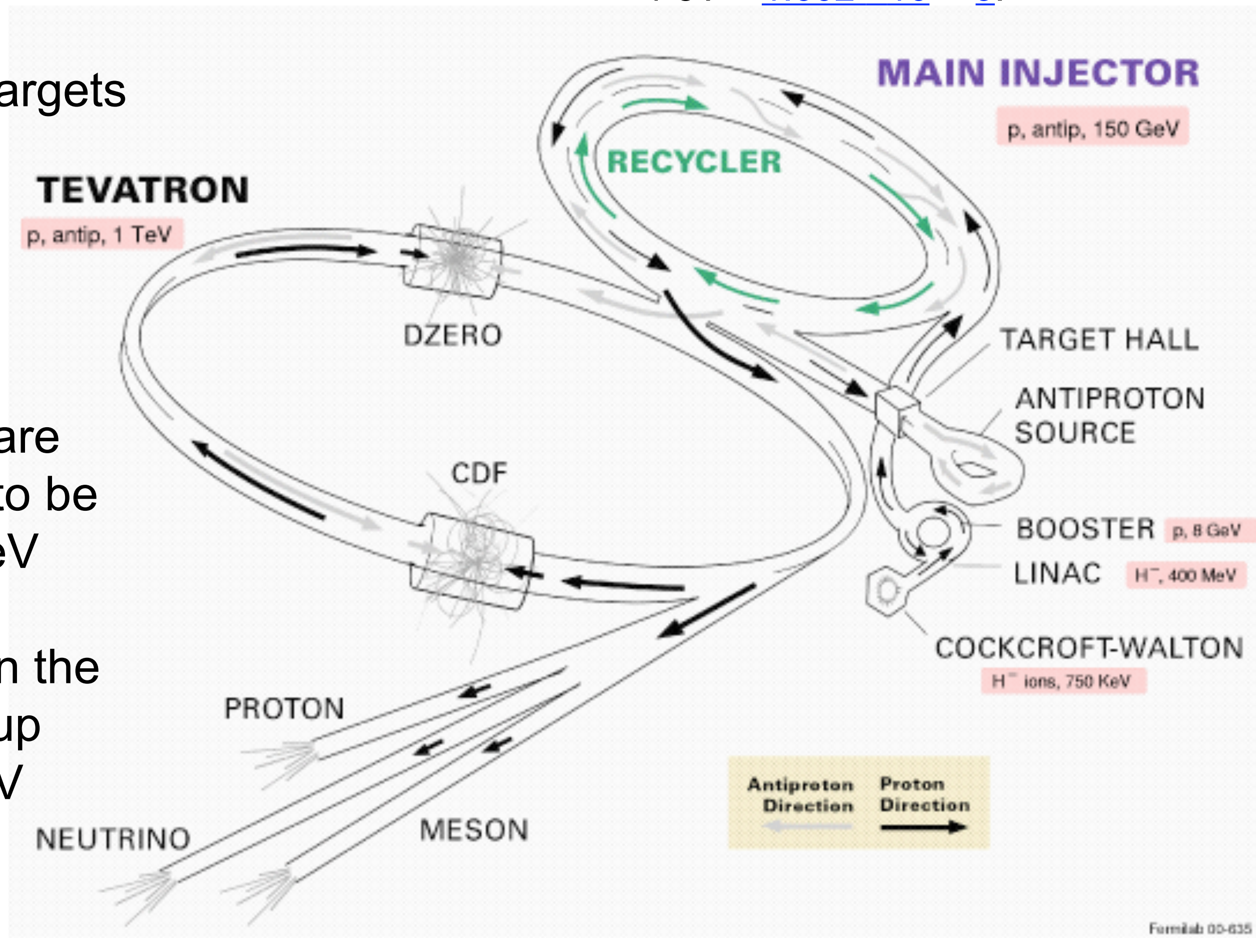
At Fermilab, we start by accelerating protons in the C-W (750 KeV) to the Linac and Booster (up to 8 GeV)

Some protons hit (gold) targets to make antiprotons

Antiprotons are stored (precious!)

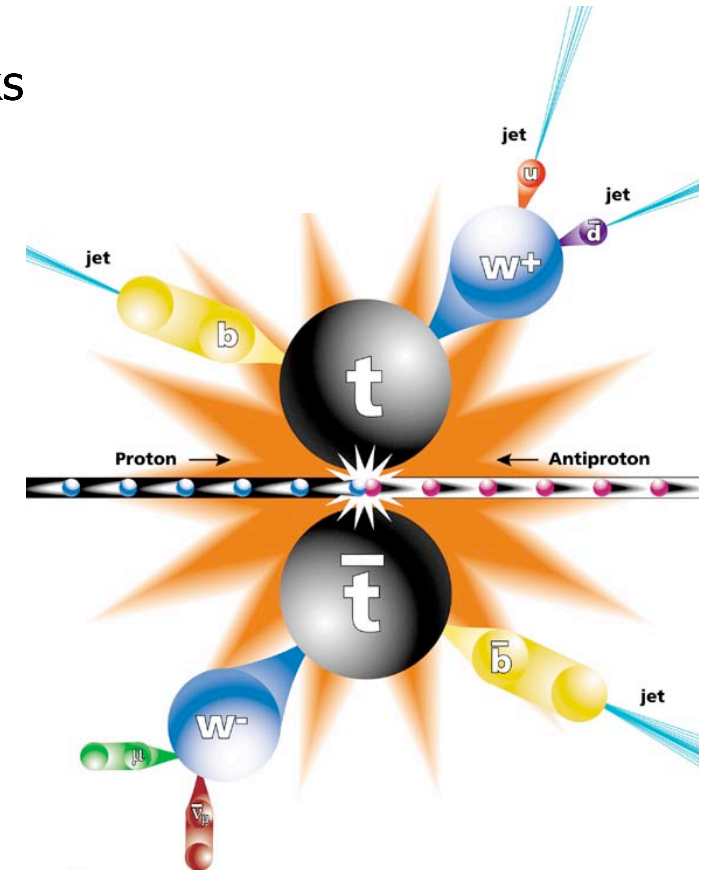
Protons and antiprotons are sent to the main injector to be accelerated up to 150 GeV

They finally get injected in the TeVatron, which ramps up the beam energy to 1 TeV



Proton-(Anti)proton Collisions

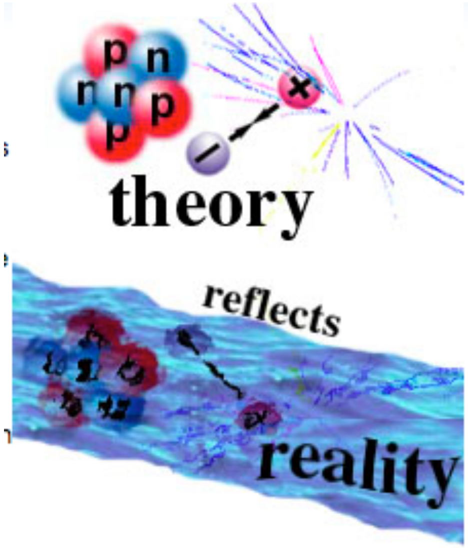
- Collisions:
  - At high energies we go inside the protons and antiprotons where we collide the internal quarks and gluons
- $E = mc^2$
  - Energy and mass are equivalent. With lots of energy we can produce lots of particles
  - 0.54 -0.63 TeV (SppS)
    - 1.8 -1.96 TeV (TeVatron)
      - 14 TeV (LHC)



- Production
  - In the collision process we can produce several types of particles and study their properties
- Decay
  - Some particles decay and the study of their daughters gives us insight on the nature of the interactions

Working at a collider

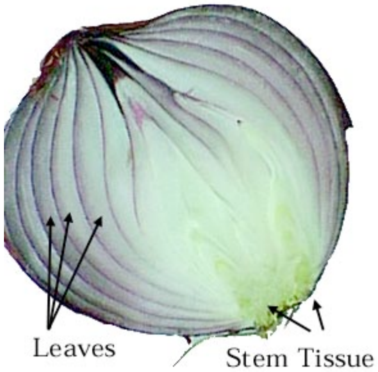
- To study all these collisions, scientists work in a very large team (collaboration)
- Some people build the detector (engineers and physicists) while others write the software to run it.
- They all take shifts to run the detector (24/7) while taking data and collecting the interesting collision events that will be analyzed.
- Events are analyzed to check theory against reality and to look for something new and unexpected



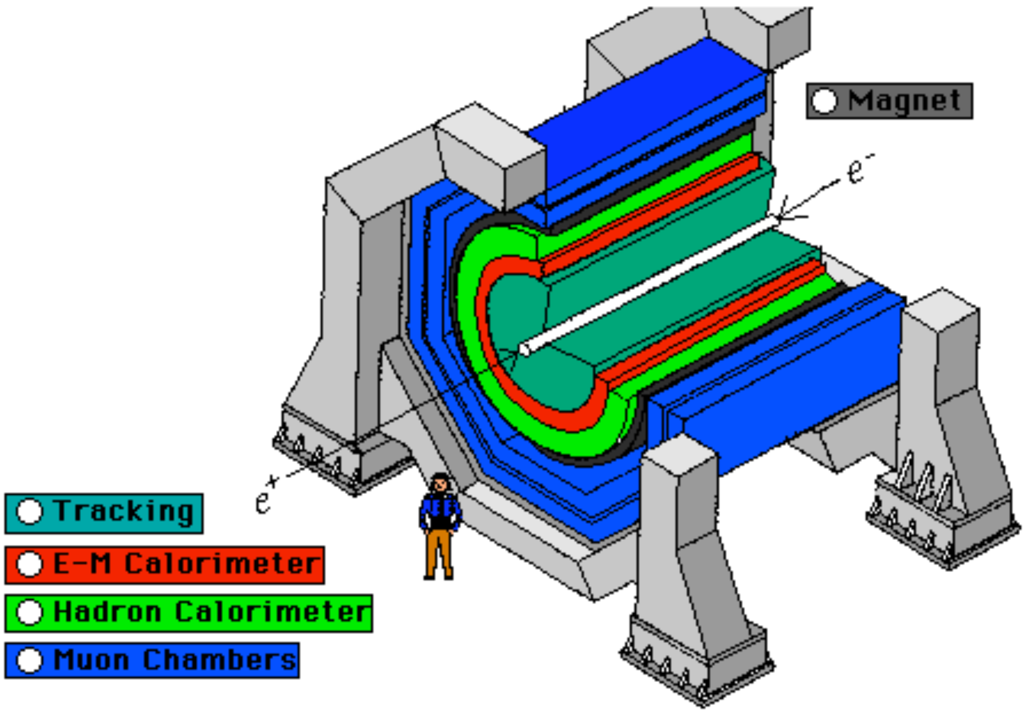
The Detector

The Experiment studies collisions between protons and antiprotons

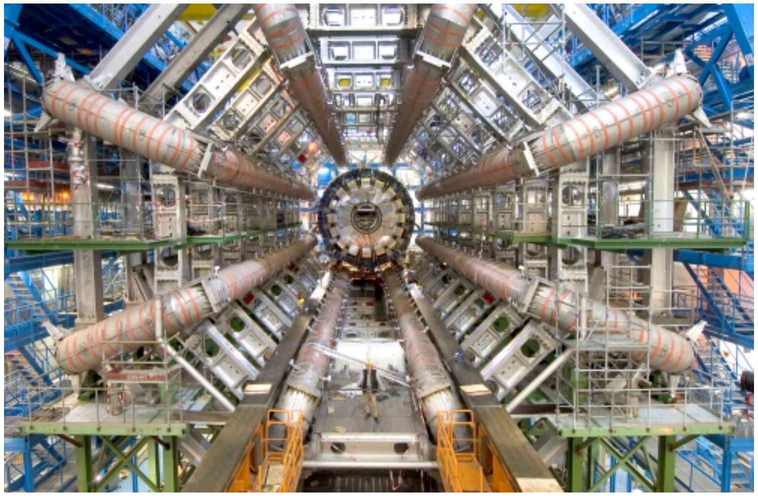
- Only interesting events are selected out of many millions
- the way the produced particle and the matter of which the detector is made interacts, is used to identify the produced particle



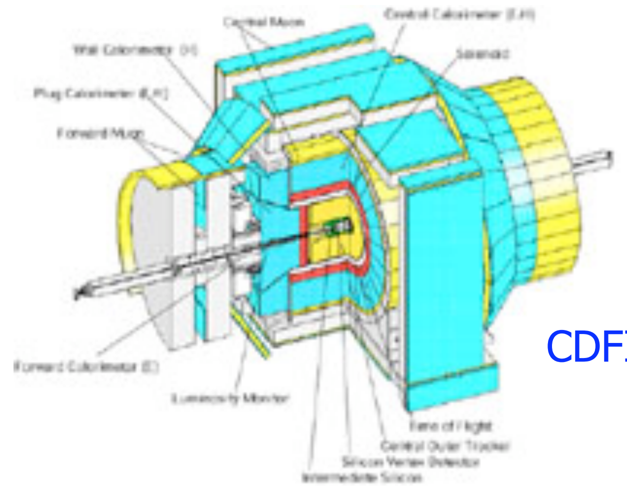
The detector is like a large onion, made of successive layers



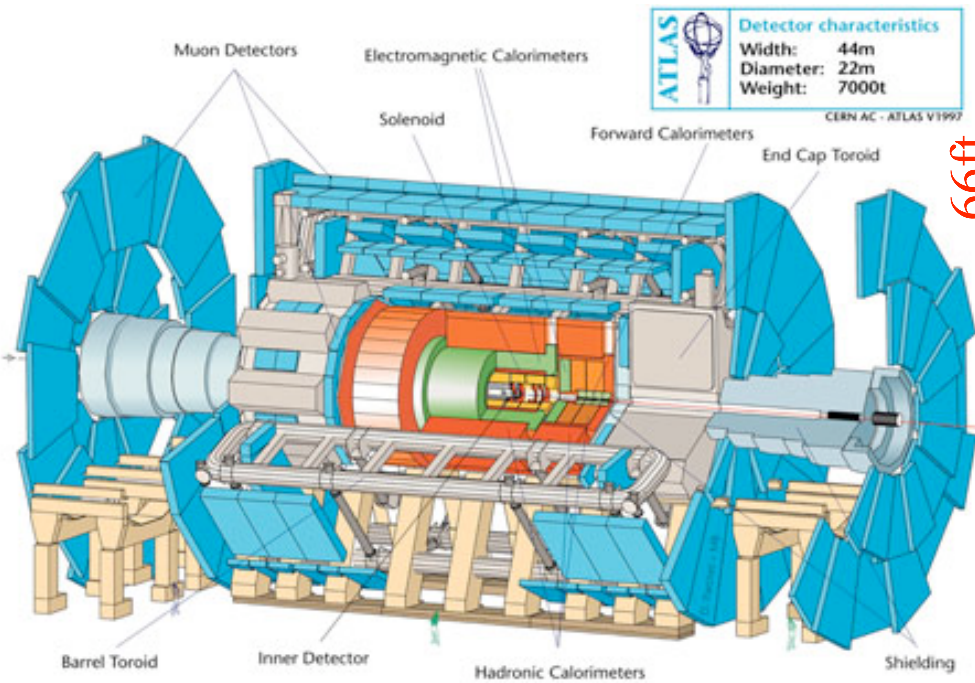
Real Detectors



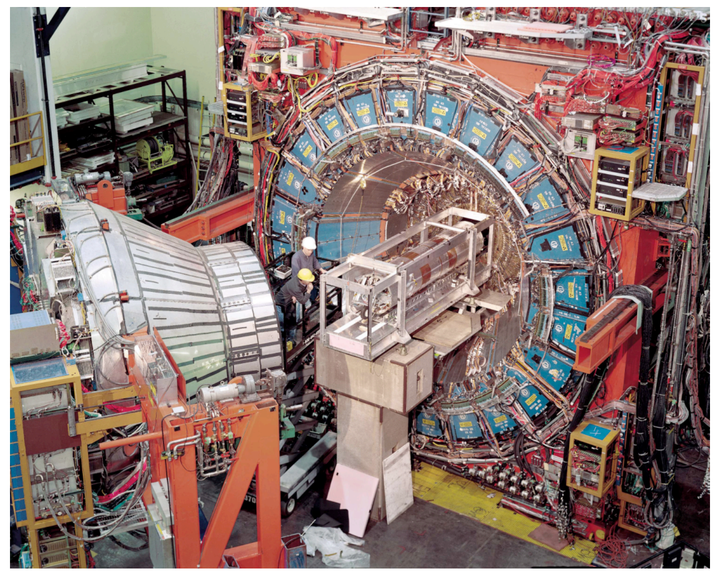
30 ft



CDFII

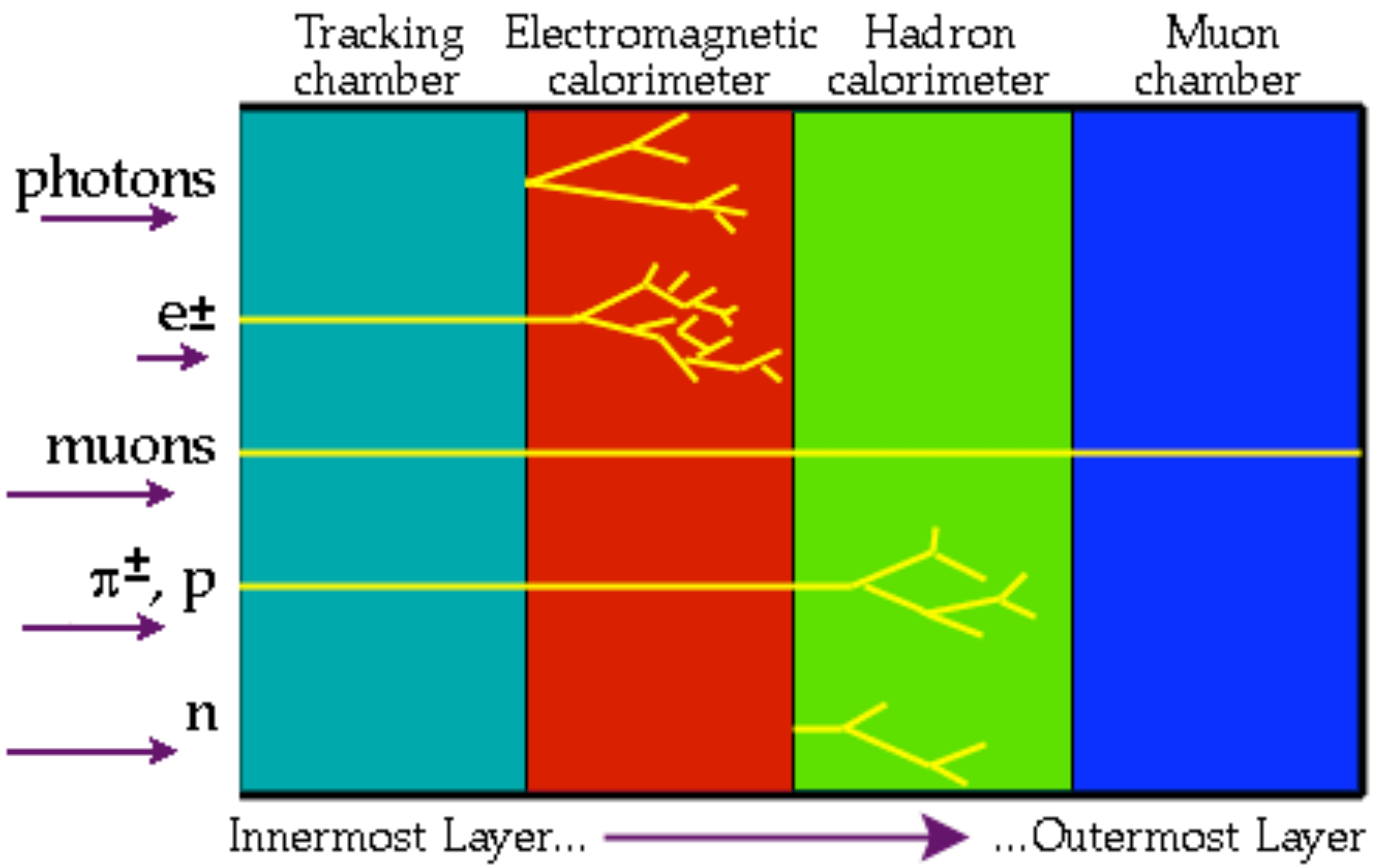


66ft



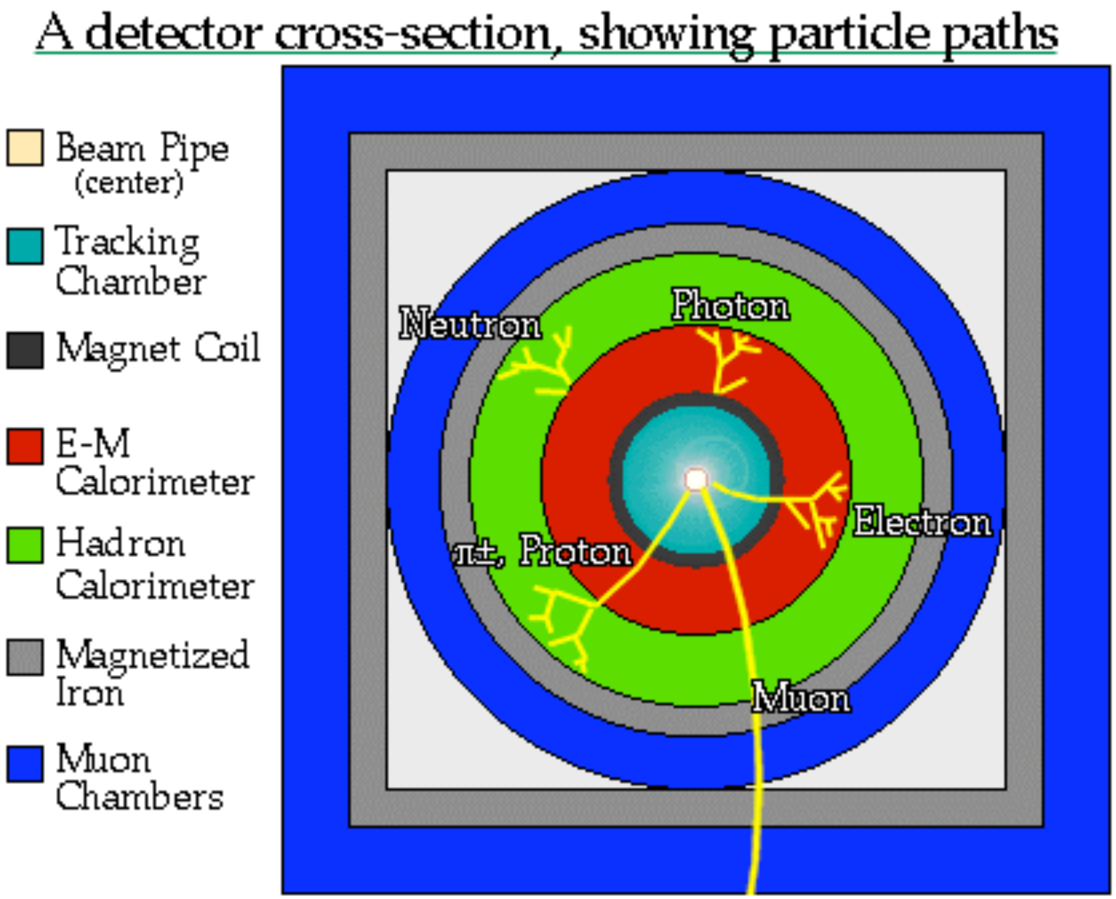
Particle In a detector

The interaction of various particles with the different components of a detector:



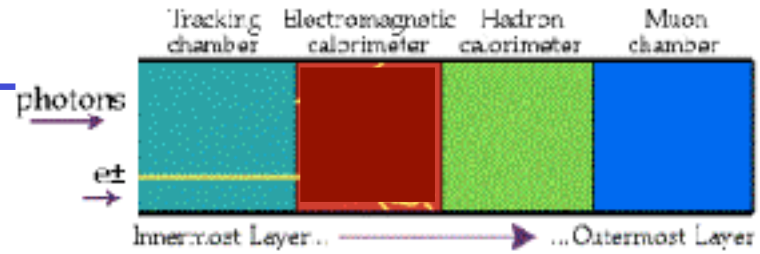
Neutrinos are not shown on this chart because they rarely interact with matter, and can only be detected by missing matter and energy. Just so you know, the pion (□) is a charged meson.

Particle detection

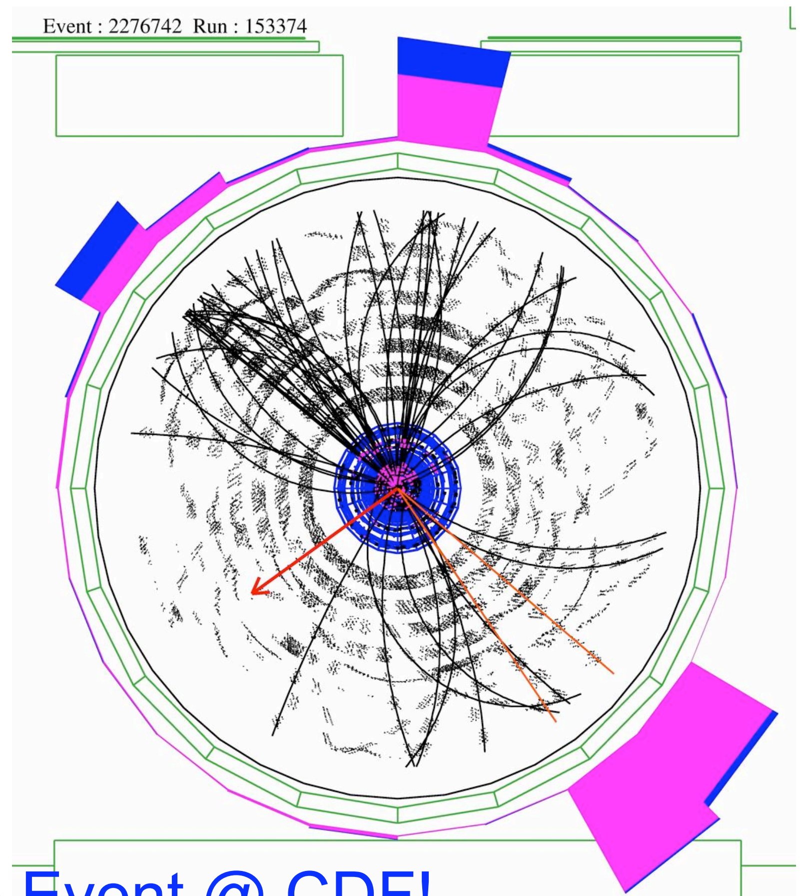


Physicists can figure out the type of particle based on where that particle appeared in the detector.

Tracks



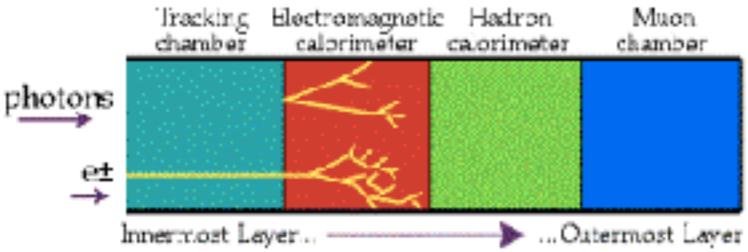
- Charged particles bend in the magnetic field
- Ions and e's knocked off gas molecules drift to the wires giving electronic signals (drift chambers)
- Hit patterns can be recognized as tracks
- The higher the energy (momentum) the straighter is the track
- Beside momentum, tracks give information about the collision point

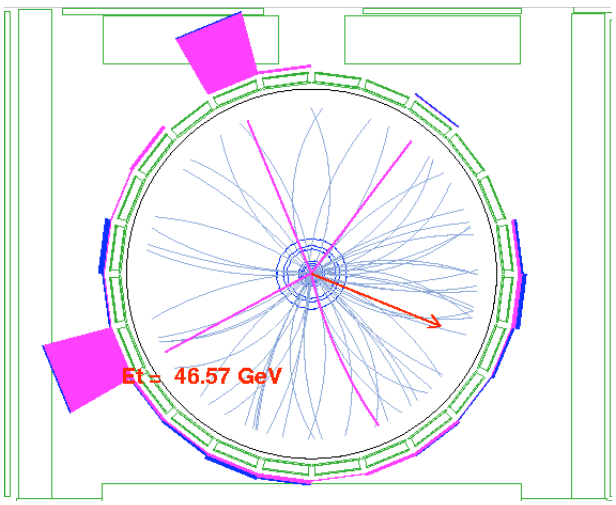


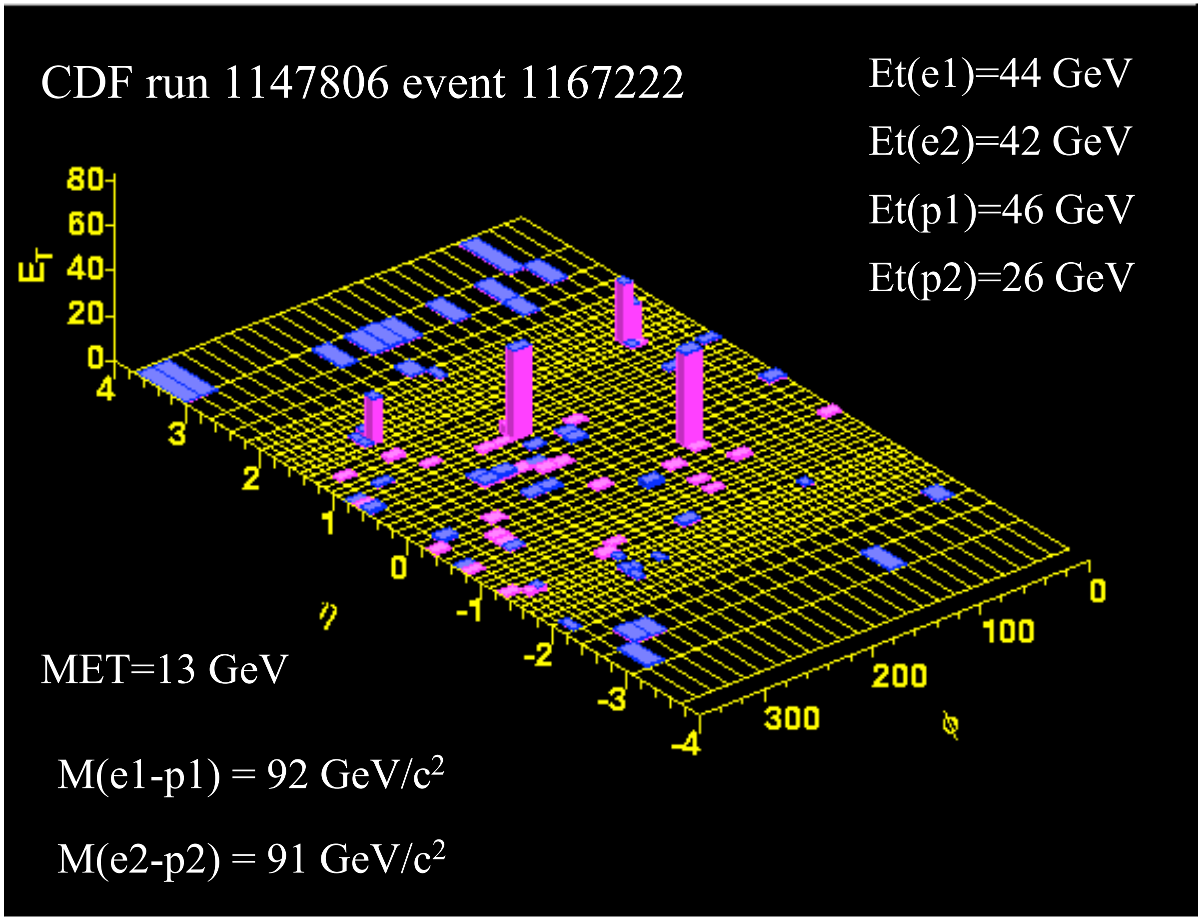
A Top Event @ CDF!

Electrons and Photons

- Electrons and Photons get easily absorbed by the calorimeter (energy deposit)
- Tracking association gives the ability to identify a charged particle: the electron.

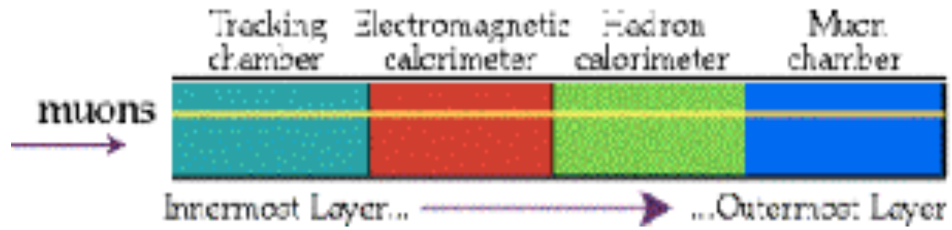






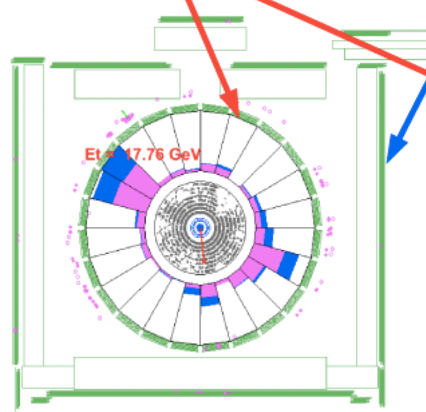
Muons

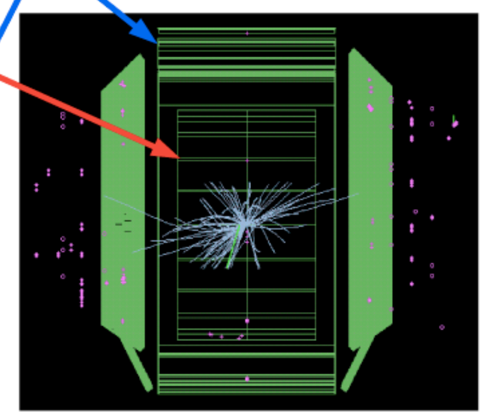
- Muons can penetrate lots of material before getting absorbed.
- Easily identified as coincidence between tracks and hits in the outer layer muon chambers: minimum ionizing particles or MIP



CMP
|eta| < ~0.6

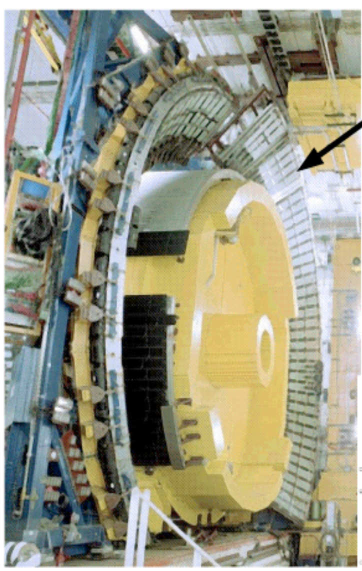
CMU
|eta| < ~0.6

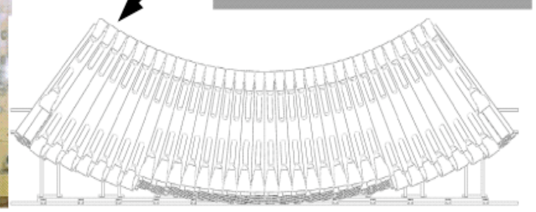




CMX
0.6 < |eta| < 1.0

CMX Miniskirt:
Wedges 16-19

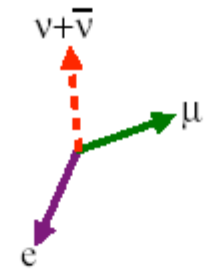


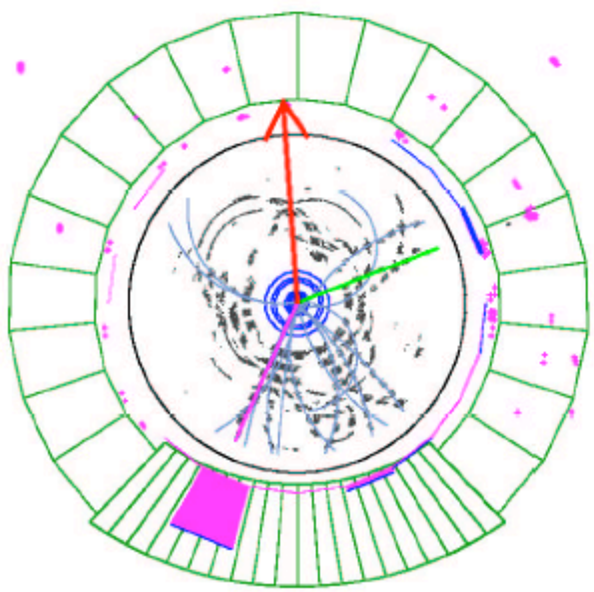


CDF Muon System

Neutrinos

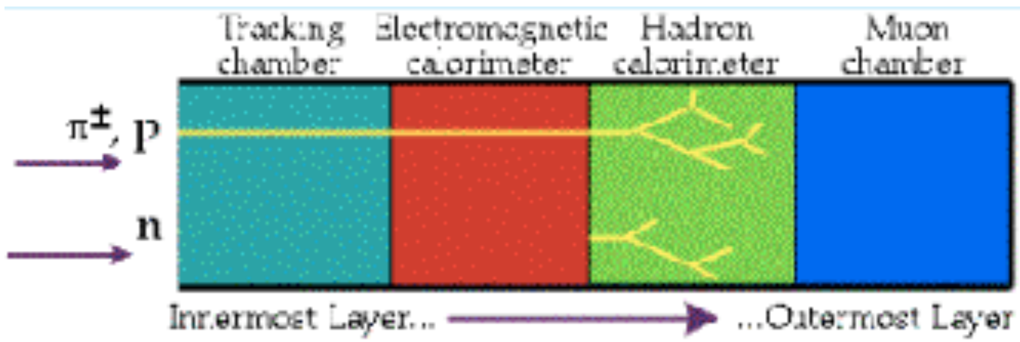
- Neutrinos rarely interact at all.
  - Since they have no charge, there is no track associated to them.
  - They don't leave energy in the calorimeter
  - They leave the detector undisturbed…
- <u>The presence of the neutrino is inferred by its absence!</u>
- We deduce the presence of neutrinos by calculating the missing energy to the total energy of the event.

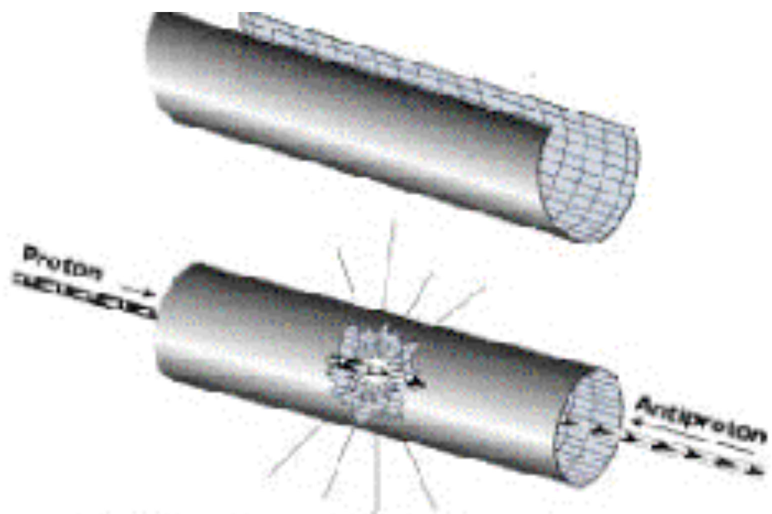


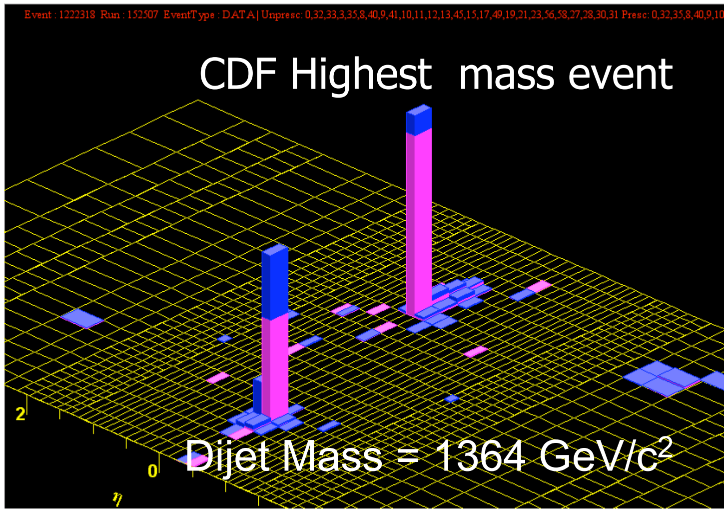


Jets

- A quark or gluon flying out of the interaction point will generate lots of hadrons moving in the same general direction: a jet.

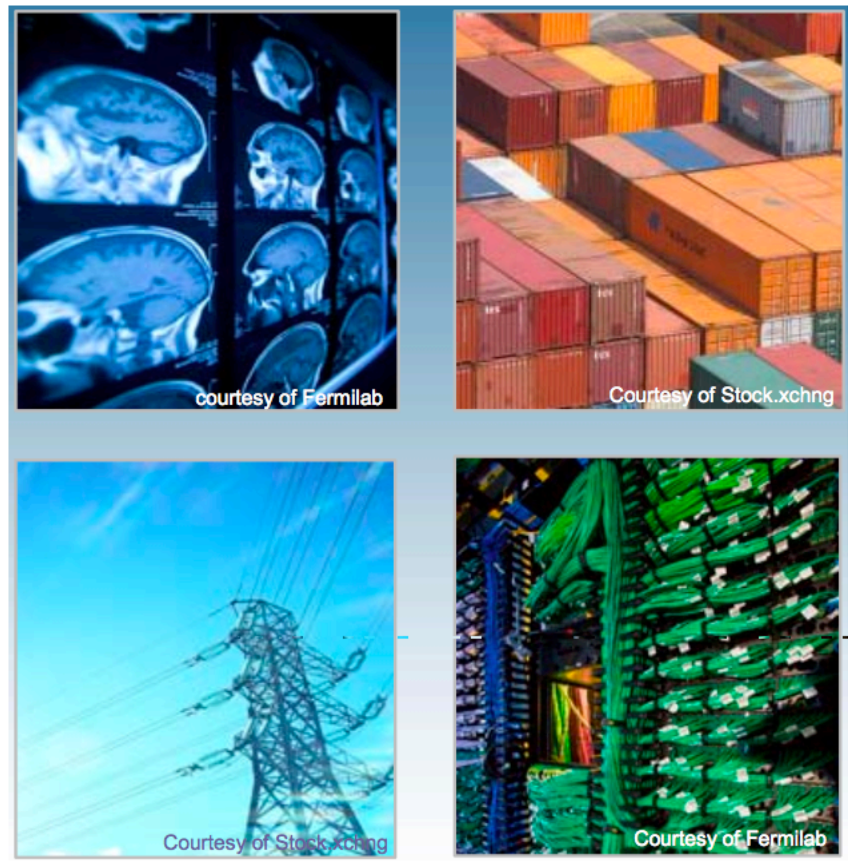






The benefits of particle physics

- The bold and innovative ideas and technologies of particle physics have entered the mainstream of society to transform the way we live
- Some well known-examples:
  - Superconducting technology: magnetic resonance
  - Internet and the World Wide Web
- Many more lesser-known impacts:
  - Food sterilization
  - Nuclear waste transmutation
  - Medicine
  - Theoretical models of particle physics applied to other scientific discipline as well as commerce
  - And much more….



The benefits of science

- Individual prosperity in our nation, or any nation, depends to a very large degree on people having good jobs.
- The existence of quality jobs in the decades ahead is very likely to depend on new developments in science and engineering as it had in the past century.

- Imagine living in a country where there is no electricity. Pretty much everything in your house would be at the level of mid 1850's...

- Electricity, just to mention one example so pervasive in our lives, was "invented" by physicists who were studying the composition of atoms (out of intellectual curiosity) and stumbled upon electrons and realized that they can travel and transport electricity... and the cathode tube was born and all the rest that follows. Without those physicists, we would still be in the dark...

Benefits of particle physics

Medicine
Particle accelerators and detectors first developed for particle physics are now used by every major medical center in the nation to treat and diagnose millions of patients.

Homeland Security
From scanning cargo in ports to monitoring nuclear waste, the same advanced detector technology that physicists use to analyze particles also better protects the nation.

Industry
Particle physicists rely on industry to produce and advance the millions of components that experiments require, putting companies on a fast-track towards new products and life-changing technologies.

Computing
To record and analyze the unprecedented volumes of data generated in particle collisions, particle physicists develop cutting-edge computing technology, making key contributions to solutions in computer science.

Sciences
Particle physicists need cutting-edge tools; many of these benefit other areas of science.

How to become a particle physicist

- Passion
- Intellectual Curiosity
- Ability to work in team
- Good communication skills
- Many years of school!

Science and math are the basic of everything that surrounds us.

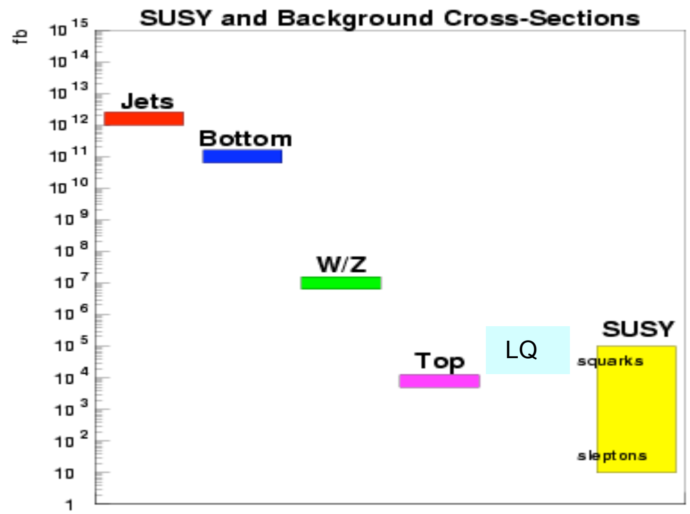
We live in a highly technological society where everything comes from discoveries in math, science and engineering.

A good training in math and science allows us to approach every problem with an analytical mind, trying to find the easiest solution which makes sense logically.


ATLAS explores...
where quarks and gluons collide...
where forces unify...
where extra dimensions may lurk...
where dark matter reigns...
to find the truly fundamental.
the ATLAS Experiment
CERN Geneva, Switzerland
ATLAS is a particle physics experiment conducted by 34 nations at the CERN Laboratory in Geneva, Switzerland. It will explore the fundamental nature of matter and the basic forces that shape our Universe. This poster is available from CERN. The ATLAS statue image is courtesy of NYCTourist.com

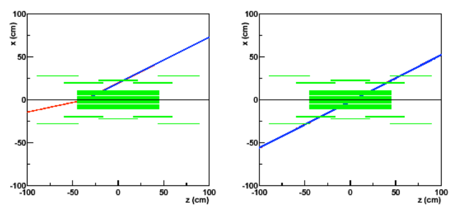
Backup Slides

Physics Processes Relative Cross Sections



Efficiency and Acceptance

- Detectors are not perfect
  - hermetic
  - Components failure
  - Over time degradation
- Geometric acceptance
  - Less than 4π coverage
  - Certain components only extend up to to certain angles
    - Silicon tracking

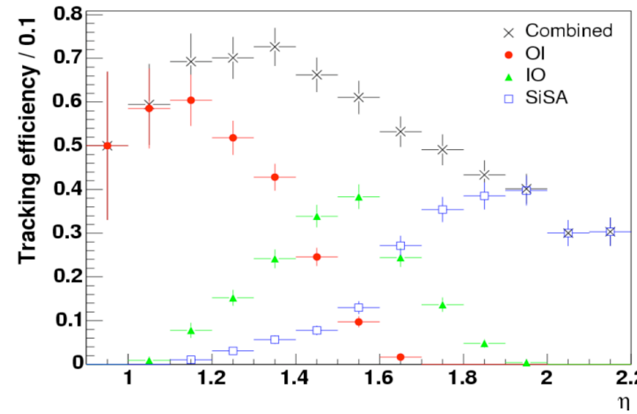


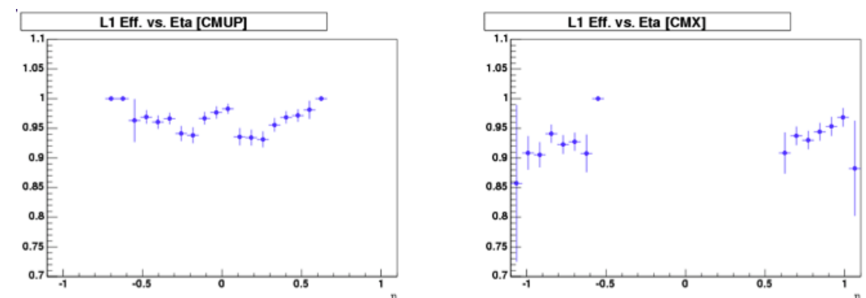
$$\eta = -\ln[\tan(\tfrac{1}{2}\theta)]$$

- Detection Efficiency
  - Trigger
  - Reconstruction
  - Identification

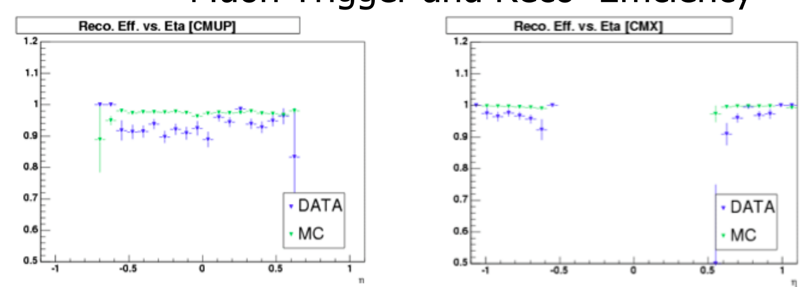
$$\boxed{\mathcal{R} = \sigma \times \mathcal{L} \times \varepsilon}$$

Tracking Efficiency





Muon Trigger and Reco Efficiency



TeVatron Top Mass, March 2007